Journal of Energy in Southern Africa

Volume 25 Number 2 • May 2014

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Challenges in household energisation and the poor

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Abstract
While the electrification of households in South Africa since 1994 has been impressive, many of the major energy services in poor households are still met by traditional fuels such as, on the Highveld, coal; in coastal regions, paraffin; and in rural areas by wood. Their use is associated with a range of challenges, from chronic respiratory tract infections to asphyxiation by carbon monoxide to massive fires that destroy not only homes but also lives. State interventions such as the provision of Free Basic Electricity are costly and do not appear to be contributing towards any solutions. The challenges are assessed, and a range of mitigations proposed.

Keywords: electrification, poverty, coal, paraffin, fuelwood, Free Basic Electricity, indoor air pollution, fires, informal settlements

Introduction

Every household needs energy services. The most basic services involve cooking, probably followed by lighting, water heating and space heating, although the need for space heating depends largely on the local climate. Every householder faces decisions as to how to obtain these services. For the wealthier, convenience is almost as important as cost; for the poor, cost dominates. This is not surprising, as it is clear that the proportion of household income expended on energy services is greater in poorer households than in wealthier. Many wealthy homes will not expend more than about 2% of their income on their energy services; in the poorest homes, as much as 7% of their income is devoted to cooking and staying warm. In disposable income terms, the proportion is much higher.

Studies of the very poorest homes have shown that, where climatic conditions are such that space heating is not vital, a minimum of about 1000MJ of energy per month suffices for basic needs. Where space heating is vital, then the home must find a minimum of about 4000MJ per month (Williams, 2004). The question facing the householder is how best to access this energy at the lowest possible cost. The decisions made have a major impact on life and health. Household energisation is therefore a very significant contributor to the ongoing trap of poverty. Accordingly, in this contribution we study the nature of the decisions facing the poorest householder, and the impacts on life and health.

Options for meeting the basic energy needs

Rural

In rural areas, the poorest homes can still access biomass, which is generally a 'free' fuel, although, in places where population growth has increased the demand on this fuel, it can start to take on a cash value. But whilst it is generally free, collecting the fuel involves commitments in time and energy that are far larger than many realize. In studies in rural KwaZulu-Natal (Statistics South Africa, 2008) harvesting of fuel wood started as early as 02h00 and finished as late as 23h00. In winter, wood consumption averaged about 600kg/month although some households got by with about 300kg/month. In summer, the consumption was about half that of winter. The wood was rarely completely dry, so

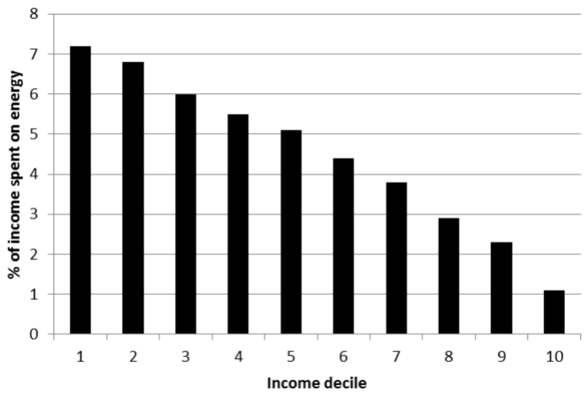

Figure 1: Percentage of income spent on energy as a function of income
Statistics South Africa (2008)

probably had a higher calorific value of the order of 12-13MJ/kg.

While this rural community relied largely on wood for its energisation, it made use of other fuels, particularly paraffin, primarily for cooking when it was raining. More than 10% of the homes had an LP gas cylinder, used for cooking on social occasions. This was remarkable, as the nearest source of gas was nearly 40 km away.

In the 2007 Household Survey (Williams, 1994), 13% of all households reported cooking on wood and nearly 20% relied on wood for space heating. Nearly 10% of all homes had no space heating at all. There was no direct disaggregation into rural and urban populations, but the provinces having the largest rural population made up the bulk of the wood users. For instance, in Limpopo, 52.5% of the population cook on wood, 24% in the Eastern Cape and 19% in each of Mpumalanga and KwaZulu-Natal. One reason why the wood use in Mpumalanga and KwaZulu-Natal is lower than in the other two rural provinces may be that over 10% of the homes in each province cook on coal.

Urban – coal

To turn now to the urban environment, there are marked geographic differences. On the Highveld (i.e. most of Mpumalanga, Limpopo, Gauteng, North West and Free State) and in parts of KwaZulu-Natal, coal is widely employed among the poor for cooking and space heating. The poorest employ an *mbaula*, a metal drum with a simple grid to support the coal, and holes in the side of the drum to admit air. Typically the *mbaula* is lit outdoors, and allowed to burn until it has almost finished smoking. It can then be used either outdoors or indoors for cooking, and finally is taken indoors for heating. As there are rarely chimneys in the homes, indoor air conditions with open braziers of coal burning for warmth are appalling. Some measurements revealed as much as 1600ppmv CO (2000mg/m^3), well above levels at which fatalities are observed (WHO, 2010). Indeed, in winter in the Highveld, studies of death notices in the Soweto, Johannesburg, newspapers in the 1990's showed that, during the winter months, there were typically three families a week in which every member died 'accidentally' during the night.[1]

However, the problems caused by *mbaulas* are self-evident, and most families, as soon as they are able, invest in a cast-iron stove. These stoves were actually designed as wood burners – the hearth is long and narrow to accept pieces of wood – but they burn coal satisfactorily once it is lit and has been burning for a while. During the initial phase of combustion, however, the fire smokes badly, and it is only once flames are observed over the whole bed of coal that smoke emission dies down. Eventually the flames die down and there is more smoke, albeit at a far lower level than soon after ignition. The stoves have chimneys, so the smoke does not affect the indoor air quality severely – but on a cold Highveld day in the townships, it can be dark at noon from all the smoke.

The smoke not only presents a health hazard (it is rich in polyaromatic hydrocarbons), but it also represents an economic loss. Captured smoke amounted to about 15% by mass of the coal but carried over 20% of the heat content of the unheated coal.

The coal that is burned is of surprisingly high quality. The users will not accept less than a B grade, and prefer A grade.[2] The size is also important. The *mbaula* requires a -75+25mm 'cobble';[3] anything smaller creates too large a pressure drop and cuts the air flow, so preventing efficient burning. The stove needs a -25+12mm 'nut'; the addition of the chimney improves the draft and so allows a smaller coal to be used. Of course, this requires the chimney to be in reasonable condition. Unfortunately, most chimneys are made from galvanized steel <1mm thick, and are soon holed. Replacements are surprisingly costly, so users tend to adapt to poor burning until the chimney has almost collapsed.

The distribution of coal is an industry in itself (Qase *et al*., 2000). About five mines produce the coal, which is stockpiled during the summer months. The first cold day of winter sees queues of 30t coal trucks at the entrance to each mine. The trucks deliver primarily to individual merchants, but about 30% of the coal goes to wholesalers. The coal is primarily sold bagged in 50 kg sacks, and usually screened in some way before bagging, to remove most of the fine material generated during transport. In country towns, the fines are sometimes added to dung cakes to improve their combustibility. House-to-house deliveries are via a light truck or horse-drawn cart. Coal consumption is several bags a month in winter and usually less than a bag a month in summer, per household (Qase *et al*., 2000). Some break-bulk occurs, with a street market in 5 and 10 litre paint cans or hubcaps full of coal.

A really remarkable finding was that the cast-iron stove was one of the earliest purchases many recent migrants to the cities made. A second-hand stove sold for at least R2 000; an entry-level new one cost R4 000. Many coal merchants ran micro financing schemes to assist householders to purchase the appliances. Investigation gave some indication of why such expensive units were desired. They were multi-purpose, providing cooking, space and water heating, and even garbage disposal. Examination of the Soweto waste stream in winter showed that it contained essentially no combustibles (Personal communication, 1993). But above all the cast-iron stove provided a social centre, where people would meet.

In total, households consume about 1 million tons of coal annually (Qase *et al*., 2000). The inefficient combustion means that this tiny fraction of all coal burned in South Africa is responsible for 40% of the total particulate load in South African skies.

Urban – fuels other than coal

Outside the areas with ready access to coal, paraffin (kerosene) is the urban choice of fuel. It is burned primarily in wick stoves and heaters, although about 1 in 10 paraffin users have a pressurized appliance of the Primus type. About 400 000t of paraffin reaches this market annually, and the average user burns about 5 litres per month.

The problems paraffin use causes are manifold. Because much is sold in litre or smaller lots, not only is there risk of contamination, but ingestion is common. Children associate such bottles with cool drinks, and if they drink it, there is a risk of choking, when a few m*l* reaches the lungs. The paraffin attacks the lining of the lungs, and causes pneumonia that often leads to death.

The problems caused by the appliances are even more severe. The wick stoves in particular suffer from numerous design deficiencies. They can heat the fuel in the fuel tank to above the flash point, and if that occurs there is a risk of a very severe fire, in which the hot paraffin burns at a rate sufficient to give over 1MW. At that heat rate, the temperature inside a typical home will exceed 400°C within 40 seconds, and the home will be destroyed within 15 minutes. The radiant heat from such a fire will ignite nearby structures, so that it is not uncommon for 'shack fires' to involve several hundred dwellings at a time. There are no official statistics, but it is estimated that between 50 000 and 100 000 homes are destroyed annually in South Africa in this way. In one township, Duncan Village (a suburb of East London), some residents had seen their homes incinerated every year for four years.

The ferocity of these fires is such that people are regularly trapped inside their homes. In one study, it was found that it was rare to find more than one infant surviving such a fire – the parents did not have time to save more than one child. Several thousand die annually, and more suffer extensive burns. In Cape Town, the Red Cross Children's Hospital has developed a worldwide reputation for its skill in rehabilitating severely burned children. The Paraffin Safety Association has co-operated with several hospitals to establish a database of burn injuries – while there is a high degree of paraffin-related injuries, a surprising number come from other sources, including electricity, and burns from cooking utensils that are knocked or pulled over are common.

The safety of the appliances has been addressed by the SA Bureau of Standards. SANS 1908 and 1243 concern non-pressure and pressure-type appliances respectively. Both standards are now compulsory in terms of the regulations of the National Regulator of Compulsory Standards. Frustratingly, appliances meeting these standards have not been developed, and accordingly, there is a black market in illegal, unsafe appliances. Actions to seize and destroy imported cargoes have been widely publicized, but the trade continues. The only effect of the standards has been to push up the price of the illegal units. A stove used to cost about R25; it now costs over R100. The metal in these appliances is typically a 0.3mm sheet, and it corrodes rapidly in use. The life is further shortened by the owner using water to extinguish the flame that persists after the appliance is nominally switched off. Few appliances have a lifetime of more than 6 months if used daily. Towards the end of their life, the risk of fire increases substantially due to mechanical failure of the corroded parts.

In spite of these risks – which are widely recognized by the users, even in country districts (Williams, 1994) – the wick stoves meet the needs of the poor. One of their features is that, unlike the somewhat better designed pressure stoves, the heat can be reduced to permit simmering. As many staples require slow cooking, this feature means that the wick stoves are preferred and are actually more economical in use even though they are significantly less efficient thermally than the pressure stoves.

Another feature making paraffin the fuel of choice is the ability of users to trade in cupfuls of paraffin. Indeed, this is an often unrecognized need of the very poor – by the very nature of poverty, they may need to have energy supplies in very small quantities to cope with daily needs. Paraffin allows this readily, and we have already seen how coal can be sold in hubcaps full. It is one of the disadvantages of the next fuel we must consider, namely liquefied petroleum gas, known as LP gas or LPG.

Comparatively little LPG reaches the poor, which is surprising, as other societies at a stage of development similar to South Africa have found it the urban fuel of choice (Lloyd & Rukarto, 2001). The primary reason for this is the cost of LPG. The distribution chain from refinery to market place is multi-stage, with mark-ups at each stage. In one study, it was found that in China the street price was ~10% above the refinery gate price; in South Africa, it was ~250% of the refinery gate price. Part of the problem is the limited size of the market; part is monopolistic practices justified on grounds of safety (the safety record of LPG is exemplary, and highlights the hazards of paraffin); and in part it is the result of distribution having developed to service the LSM 5-7 group rather than the poor. The last could be considered a hangover from the days of *apartheid*. The Department of Energy is aware of the difficulty, but has failed to address the challenge since its first attempt in 1998. At present only about 100 000t/a finds its way into the whole of the domestic market.

The benefits of the use of LPG were apparent in 2007 when power from the nuclear reactor at Koeberg was lost. Eskom arranged to swop 100 000 cheap electric stoves for an LPG supply complete with cooker. The initiative saved 40MW of peak power, but stumbled when, in spite of demand, the petroleum industry could not supply.

Possibly because of the low national demand, the supply of LPG is limited. The only storage is an almost insignificant 5 000t at Richards Bay, a port on South Africa's east coast. Environmental approval has recently been granted for the construction of a 10 000t store at Saldanha on the west coast, and trial imports have already taken place. A company called Wild Orchard has set up a distribution network to supply gas in 5 kg cylinders to townships in the Cape at a price significantly below normal retail. This has not been without significant challenges. For instance, it was necessary to establish a store for a few hundred cylinders. The store required fire department permission, which could not be granted because the store was in an informal township, and not located on an identifiable stand. Work is in progress to allow the fire department to use GPS co-ordinates rather than stand numbers for location purposes.

There seems little doubt that if the logistics of getting LPG to low-income homes economically can be resolved, it will become the fuel of choice. It is significantly cleaner and much safer than paraffin. A range of affordable appliances can be fitted to a single cylinder. The appliances are generally more efficient than the alternatives. Control of the heat is simple and direct.

Wood finds some use in the urban environment. Some townships 'harvest' broken pallets from nearby industries. Removal of invasive acacia species under the "Working for Water" Programme has stimulated an industry in harvesting the cut timber for fuel, but this is probably only a short-term venture. There is concern about chemical preservatives in industrial timber collected as fuel, and its use in open fires for cooking is discouraged. However, because of limited availability, wood does not feature strongly in towns.

We must consider electricity. The electrification programme since 1992 has been an outstanding success. Nearly 80% of all households have access to grid electricity. However, the impact has been significantly less than was originally expected. A recent review (Lloyd, 2012) showed how uptake was slow for nearly a decade after first gaining access to electricity. The first use was for lighting and low power appliances such as entertainment and communications. Household demand was often less than the 50kWh/month of free basic electricity. After a year or so, small appliances such as kettles and irons came into use, and household use grew to the order of 150kWh/month. It took several more years before larger white goods such as refrigerators became common, and use grew to the order of 300kWh/month.

This slow uptake caused some grave problems. Both Eskom and municipalities invested quite heavily in the distribution infrastructure. Thereafter the revenue stream was far lower than had been anticipated, and there was considerable financial stress, particularly at the municipal level. The problem was exacerbated by the fact that many municipalities use electricity revenue to subsidize other municipal services. Lower-than-expected electricity revenues therefore had repercussions across the whole realm of service delivery. The fact that some households were being subsidized with free basic electricity aggravated the problem.

These problems are still being worked out. The Government has made several attempts to resolve the problems of the distribution industry. In 2008 the company EDI Holdings, which had been set up to oversee the restructuring of the industry, estimated there was a R25 billion shortfall in maintenance and refurbishment of the distribution system. SALGA estimates this has grown by at least R2.5 billion a year since then. The Department of Energy is reputed to be preparing a Cabinet minute to establish a fund – but it started the preparation in 2010.

Part of the problem is that Eskom distributes 55% of the nation's electricity to 45% of its customers; the municipalities buy electricity from Eskom and distribute the balance. Eskom by and large distributes satisfactorily; its distribution network is ageing but reasonably well maintained, and it is quite active in ensuring revenue collection – only payments from Soweto remain problematic. In contrast, the municipalities are struggling to maintain their distribution assets, and revenue shortfalls presently amount to billions. Even major metropoles such as Johannesburg are failing in what should be a reasonably straightforward business.

Ultimately it is the poor who suffer most from these problems. 50kWh/month of free basic electricity is wonderful – as long as there is electricity! When there is none, the free benefit is worthless. With hindsight, the provision of free electricity was probably a mistake. First, it gave people the impression that it could be free, which encouraged the culture of non-payment. Secondly, those who were not yet electrified were aggrieved at the double benefits enjoyed by those who were. Thirdly, the impression was gained that access to electricity was some form of right. It will take a generation to undo the damage that has been caused.

However, something unexpected emerged from the electrification programme – entrepreneurship ruled. As the programme electrified more and more homes, there were others just beyond the boundary who sought that barest minimum, to give them light and to recharge their cell phones. They could not wait. Illegal connections sprang from the electrified homes towards the nominally unelectrified. Leads of over 150 m were identified, with several homes along their route sharing the benefit (Lloyd *et al.,* 2007). Of course, in some cases these leads are outright theft, which remains a problem throughout many townships, but the majority pays for the service they receive – even if they use funds collected from those to whom they have sold on.

Finally there are options that we have not explored in depth, but which deserve mention:

- *Photovoltaics:* These find some use in rural areas where there is no grid supply. To many, this is not real electricity – there is only sufficient power to charge a few small batteries and perhaps watch low-power television at night. Many systems have been 'acquired' from remote power systems installed by Telkom or Eskom – even self-powered emergency telephones on highways have lost their power this way. It says something about the ingenuity of the thieves that they can install and maintain their own mini-power-plant.
- *Alcohol gel fuel:* This enjoyed a brief period of excitement, if only because it promised a biofuels alternative. However, a clean burn requires mixing of the fuel with air, and it is impossible to mix a gel with air. Instead the gel fuel relies on the vapour pressure of alcohol and the convection caused by burning to mix the fuel with air. An extensive study identified only one appliance that gave a reasonably clean burn (Lloyd & Visagie, 2007). Also, the heating value of the alcohol is significantly less than that of paraffin, so cooking required a larger volume of fuel, and as it was priced at the same level as paraffin per unit volume, the users soon became disenchanted.
- *Solar cooking:* Numerous expensive pilot tests have succeeded in showing that this is no solution. At best, once the investigators depart, the users learn to cook when the conditions and their day's duties allow, otherwise the cooker merely takes up valuable space in an already crowded dwelling. An unpublished study suggested that there were two primary reasons for the failure of this 'solution'. Firstly, cooking is a social activity demanding personal involvement and personal attention. Mixing something up and leaving it out in the sun for a few hours gives no personal satisfaction, no opportunity for a quick taste to see how the flavour and texture are developing. Users reported distinct unease when using the solar cooker. Secondly, theft, though rare, occurred, and once the risk was recognised, solar cooking fell out of favour.[4] A third and lesser reason was unexpected cloud, leaving an uncooked meal and an unhappy, hungry family.

Discussion

Many of the fuels employed in poverty pollute the environment, particularly the indoor air. This causes numerous respiratory problems, and the World Health Organisation estimates that it is the third most common cause of death in infants worldwide. Learning how to use them cleanly, if they are accessible and affordable, would obviously make a significant difference. However, it is not simple, as the example of coal illustrates. The users have made a considerable investment in the appliances employed to burn coal, and are obviously most reluctant to change, particularly when the stove provides so many services. The solution must be to remove the primary cause of the problem, which is the smoke. This is the solution that all developed societies which passed through this transition adopted. Britain, for instance, banned the use of raw coal domestically after the disastrous 'pea-soup' fogs of the 1960's. As a transition fuel, they developed smokeless fuel, which was coal from which the volatile component had been largely removed. It is the volatile components of coal which form the heavy smoke as the coal is heated towards the ignition temperature.

During the 1990's the Department of Minerals and Energy carried out extensive tests on low-smoke coal. If the volatile content was reduced to between 8 and 10% by mass, the fuel remained easy to ignite but the production of smoke was minimized. A large-scale demonstration was carried out in Qalabotjha near Villiers in the Free State, when for three weeks, the coal merchants distributed nothing but the experimental fuels (Lloyd, 1998). Unfortunately, the fuel had been ordered at too fine a size (-15+6mm). It had to be screened to produce a +10mm fraction which was found satisfactory. However, the quantity of fuel available was obviously reduced by screening, and towards the end of the experiment many homes reverted to conventional fuel. Nevertheless, the air quality was markedly improved during the course of the experiment, and the level of respiratory complaints reported at the clinic dropped markedly.

Attempts to proceed to the manufacture of low-smoke fuel failed, and the Department was then diverted by the rediscovery of the so-called Scotch method of lighting a coal fire, by igniting the coal from above and having the fire to burn downwards. In this way, the coal was not heated from below, and the volatiles driven off by heating were combusted rather than being emitted as particulate smoke. The Department promoted the method as

Basa Mjengo Ngogo, the Old Woman's Fire. While it demonstrably reduced the smoke from an *mbaula*, it was not effective in stoves (Leiman *et al.,* 2007).

A business plan for low-smoke fuel was developed for the Department. It foresaw three factories producing low-smoke fuel by heating the coal to about 400ºC, at which point the volatiles would be driven off and burned to provide the heat. Once the volatile content had dropped to below 10%, the fuel would be discharged, cooled away from contact with air, and stored until ready for sale. Coal would be delivered to the factories by rail, and distributed by road as at present. The factories were sited such that the haulage distance to the coal markets was much less than it is at present, with considerable savings on transport costs. The factories would operate year round, and the fuel stockpiles would therefore be created during the summer months at the factories, rather than at the mines. The whole process would be financed by a modest levy on coal sold into the domestic market, which would enable the low-smoke fuel to be sold at a price slightly below that of coal in the early years, when the volume of low-smoke fuel was small. As the volume built up, the revenue from the levy would reduce but the unit cost of production would also fall due to economies of scale. At some point, it would be possible to ban all further sales of unprocessed coal into the domestic market, while the total impact on the consumer would be modest.

Fixing the paraffin problem requires a new generation of appliances. Some lessons may be learned from the Japanese market. It may come as something of a surprise to learn that the Japanese market for safe paraffin appliances is large. Safety comes at a price, and the appliances may be too costly for the local market. However, the coal stove story carries the lesson learned with difficulty by every marketer – if you can satisfy people's needs, they will find a way to buy your product almost regardless of price. The poor are aware of the hazards that the existing paraffin appliances present. It is therefore a challenge to introduce them to more expensive appliances that meet their needs and also remove their fears.

To some extent this assumes that paraffin will remain the fuel of choice in the urban environment. It is entirely possible that the LPG market may change radically. In particular, there is at present a large commercial and industrial market for LPG. However, the natural gas industry is starting to show signs of life. If it should develop, then it will certainly displace much of the LPG from the industrial and commercial markets, which will therefore remove the present constraints on its supply into the domestic market.

And, of course, with the passage of time, more and more people should make the transition to the use of electricity for most of their household energy. Dealing with the traditional fuels makes one realize just how clean, how convenient and how economic electricity really is. Indeed, if one looks at electricity from the point of view of sustainable development, it ticks all the boxes – it is ecologically friendly, it is socially progressive, and it is economic. The three legs of sustainability are balanced. Of course, some will argue that, for instance, coal mining and combustion in a power plant carry environmental costs. While that is true, the costs are nowhere near those associated with the domestic use of fuels like wood, coal and paraffin.

Notes

1. The 'accidental' death is important; no statistics were kept on the cause of death other than that it was 'accidental'.
2. There have been repeated attempts to persuade users to accept waste coal of a D or sub-D grade, all of which have failed.
3. 'Cobble' and 'nut' are terms used in the coal trade to describe products of the given size.
4. In Botswana, wild animals rather than humans found partially cooked food perfectly palatable!

Acknowledgements

I was introduced to this fascinating subject by the late Prof David Horsfall, of the University of the Witwatersrand, some of whose work I was able to take up and complete after his untimely death. Much of the coal work had the support of the late Chris Grobelaar, of the Department of Minerals and Energy as it then was, and Noma Qase was invaluable in helping to unravel the coal markets. In Cape Town, Glenn Truran, Dehran Swart and Teri Kruger of the Paraffin Safety Association introduced me to the paraffin problem, and George Tatham educated me in the wonders of LP gas. At the Energy Research Centre (ERC) of the University of Cape Town, there were numerous colleagues, of whom Mark Howells, now at KTH in Stockholm, Alison Hughes and Bill Cowan were probably the greatest assistance. Of late, Prof Ernst Uken and Prof Nico Beute, associates at the Energy Institute, CPUT, have been most supportive.

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Received 6 November 2012; revised 26 March 2014

Design of a low voltage DC microgrid system for rural electrification in South Africa

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Abstract

This project entails the design of a low voltage DC microgrid system for rural electrification in South Africa. Solar energy is freely available, environmental friendly and it is considered as a promising power generating source due to its availability and topological advantages for local power generation. Off-grid solar systems are perceived to be a viable means of power delivery to households in rural outlying areas in South Africa as solar panels can be used almost anywhere in the country. The design presented in this paper is based on the power demand estimation, photovoltaic panel selection, battery sizing and wire selection for the distribution system.

Keywords: battery storage, DC loads, photovoltaic panel and simulation

1. Introduction

Our electric power system was design to move central station alternating current (AC) power, via high-voltage transmission lines and lower voltage distribution lines, to householders and businesses that used the power in incandescent light, AC motors, and other AC equipment. But, extending the electric grid to remote rural areas is uneconomical to carry out.

Increases in global energy costs, coupled with the warming of the earth's atmosphere due to greenhouse gas, are energizing a worldwide call for clean and efficient energy sources and architectures. On the other hand, globally over 1.3 billion people are without access to electricity (IEA, 2011). Most of them live in rural and remote areas of developing countries, with a more dispersed population density; many of whom are either or below the poverty line. South Africa, for its part, has 12.3 million people without access to electricity (Weo, 2011). Meanwhile, there is an outburst of interest in the use of renewable energy source to reduce greenhouse gas emissions. Renewable energy generation typically produces DC power, making it a viable distributed source for the low voltage DC microgrid system which is viewed as the best solution of power delivery to households in outlying areas where the utility grid is out of reach.

This project entails the design of a stand-alone low voltage DC microgrid system to power a fully DC single house in outlying areas. When considering the electrification of rural areas it is important to design systems that are reliable and require little maintenance as in these areas frequent repairs and replacements might not be easy. Efficient and low power consumption DC home appliances that meet the basic needs of a simple house are considered first power demand estimation and from that a simplified solar system which consists of a PV panel, MPPT charge controller, battery and wires, is designed as a low voltage DC microgrid system to supply sufficiently the energy demand.

2. Background

Much research has been carried out into many aspects of rural electrification. One of the main aspects for the slow pace of rural electrification is simply the enormous cost associated with extending electricity grids to rural areas or establishing isolated mini power systems for rural communities (Mutale *et. al*, 2007). South Africa is a large country and has many rural areas. There is always no grid connection to outlying rural areas and many of these rural areas remain without access to electricity. Grid extension projects are time intensive and require large capital investment. Long distance needed to be covered by the grid to reach these outlying areas make it too expensive to be feasible. Moreover, as the areas are sparsely separated and have a low power demand, the expense of extending the grid may not be worth the benefit that it would bring.

Electrification of these areas requires new and cheaper technologies. It is more viable to directly use the power generated by a distributed renewable energy source nearby. This eliminates the enormous cost associated with extending electricity grids. Moreover, 12V (or 24V) DC appliances are relatively inexpensive in the concept when compared to AC appliances as they don't require buck converters to step down the 230V AC to 12V (24V) DC required by most of the appliances.

3. System design

Hybrid renewable energy systems have been accepted as possible means of electrifying rural outlying areas where it is too expensive to extend the grid to supply them. As stipulated in the introduction, the system is intended to power households, and it must be cost effective; therefore, only solar energy system is retained. Figure 1 shows the overview of the low voltage DC microgrid system.

3.1 Loads selection and energy demand estimation

The 12V DC loads in Table 1 have been selected.

Table 1: DC loads and power demand

Appliances	Power
Phocos LED lamp	2×9W
Phocos TFT-LCD TV	5W
Engel fridge SB47F	30W
Sangean portable radio	6W
RoadPro Portable Fan	6W

From Table 1, daily energy demand can be estimated. Table 2 shows daily energy consumption.

Table 2: Energy consumption

Appliances	Power
LED lights	18W ×7h
Refrigerator	30W ×18h
TV	5W ×12h
Radio	6W ×4h
Fan	6W ×7h

The energy consumption estimated in Table 2 gives a total daily average of 792Wh for a summer day.

3.2 Photovoltaic generator

A photovoltaic (PV) generator is the whole assembly of solar cells, connections, protective parts, supports etc. (Gonzalez, 2005). A photovoltaic (PV) generator converts sunlight energy into electricity. The energy produced by the solar system is reliant on climatic conditions.

A photovoltaic system consists of cells at a basic element level. These cells can be connected together in series to form modules (or Panels). Figure 2 shows a moderate model of a PV cell used in this paper.

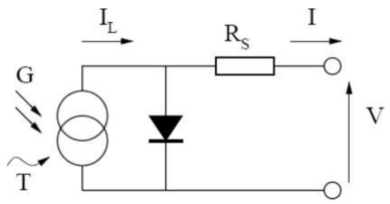

Figure 2: Circuit diagram of the PV model Aapted from Walker (2000)

This model consists of a current source (IL), a diode (D), and a series resistance (Rs). The net current of the cell is the difference of the photocurrent, IL and the normal diode current Io; the model included temperature dependence of photocurrent IL and the saturation current of the diode Io. The equations which describe the I-V characteristics of the cell are (Gonzalez, 2005):

$$I = I_L - I_o[e^{q(\frac{V+I.R_s}{nkT})} - 1] \quad (1)$$

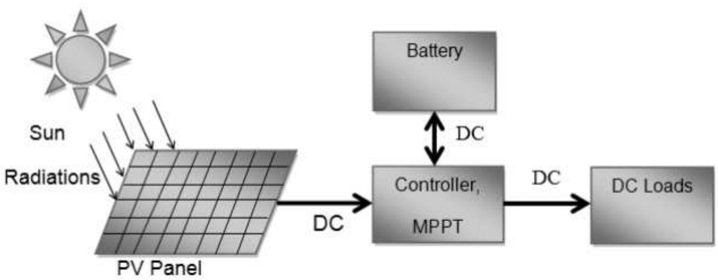

Figure 1: Model design of the DC microgrid system
Adapted from Lalwani et al (2011)

$$I_{L(T)} = I_{sc(T1)} + K_o(T - T_1) \quad (2)$$

$$I_{L(T_1)} = \left(\frac{G}{G_{(nom)}}\right) I_{sc(T_1)} \quad (3)$$

$$I_{o(T1)} = \frac{I_{sc(T1)}}{\left(e^{\frac{qV_{oc(T_1)}}{nkT_1}} - 1\right)} \quad (4)$$

$$I_{o(T)} = I_{o(T1)} . \left(\frac{T}{T_1}\right)^{\frac{3}{n}} . e^{\frac{-qV_{g(T1)}}{nk\left(\frac{1}{T} - \frac{1}{T_1}\right)}} \quad (5)$$

$$R_s = -\frac{dV}{dI_{V_{oc}}} - \frac{1}{X_v} \quad (6)$$

$$X_v = I_{o(T1)} . \frac{q}{nkT_1} e^{\frac{qV_{oc(T1)}}{nkT_1}} \quad (7)$$

Where:
I_L is the photo generated current (A);
I is the net cell current (A);
I_o is the reverse saturation current of diode (A);
q is the electron charge (1.602×10^{-19}C);
V is the cell output voltage (V);
R_s is the resistance inside the cell (Ω);
n is the diode ideality factor (takes value between 1 and 2);
k is the Boltzmann's constant (1.381×10^{-23}J/K);
T is the cell temperature in Kelvin (K);
T_1 is the cell temperature at the Standard Test Condition (STC), given as 25°C or 298K;
$I_{sc(T1)}$ is the short circuit current (A) at T_1;
K_o is the temperature coefficient of I_{sc} (%/°C);
G is the irradiance (W/m^2);
$G_{(nom)}$ is the normalized value of irradiance at STC (1000W/m^2);
$V_{oc(T1)}$ is the open circuit voltage of the cell at T_1 (V).

The Matlab script used to compute the equation (1) of the I-V characteristics is the Photovoltaic Module in Matlab by Gonzalez (Gonzalez, 2005). A typical I-V characteristic of the solar panel is shown in Figure 3. The P-V characteristics of the solar panel at two different atmospheric conditions are shown in Figure 4.

Koutroulis *et al* (2006) present the following methods of calculating the power of the PV panels at the specified temperature and the irradiance:

$$P_{mp} = N_s . N_p . V_{oci} . I_{sci} . FF \quad (8)$$

$$I_{sci} = [I_{sc} + K_o(T_c - T_1)] \frac{G}{G_{(nom)}} \quad (9)$$

$$V_{oci} = V_{oc1} - K_v . T \quad (10)$$

$$T_c = T + \frac{NCOT - 20}{800} . G \quad (11)$$

Where:
N_s is the number of series PV panels;
Np is the number of parallel PV panels;
V_{oci} is the open circuit voltage at the specified temperature and irradiance;
I_{sci} is the short circuit current at the specified temperature and irradiance;
FF is the fill factor of the panel;
I_{sc} is the short circuit current at STC;
K_o is the temperature coefficient for short circuit current;
T_c is the calculated temperature;
T_1 is the STC temperature at 25°C;
G is the irradiance;
G_{nom} is the irradiance at STC given as 1000W/m^2;
K_v is the temperature coefficient for open circuit voltage;
T is the PV operating temperature;
NCOT is the Nominal Cell Operating Temperature.

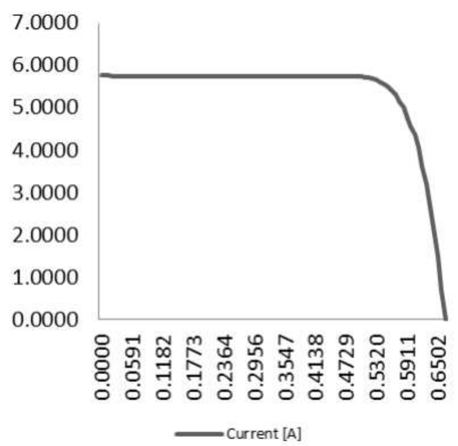

Figure 3: I-V characteristic of the solar panel

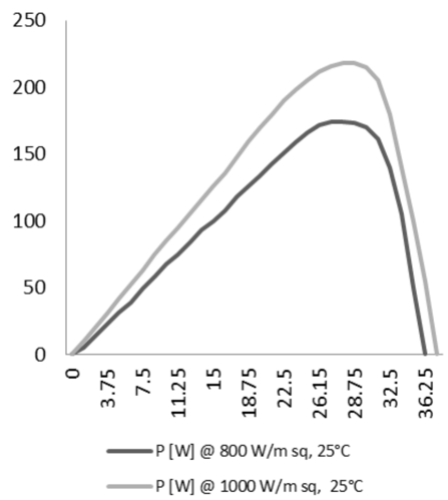

Figure 4: P-V characteristics of the solar panel

The peak power for PV sizing is calculated as:

$$Pp = \frac{Ed}{\eta_T.peaksunhours} \qquad (12)$$

With:

$$\eta_T = \eta_1.\eta_2.\eta_3. \qquad (13)$$

Where:
E_d is the daily energy demand;
η_T is the product of component efficiencies;
η_1 is the wiring efficiency (typically 90%);
η_2 is the charge controller efficiency (90%);
η_3 is the battery efficiency (typically 90%).

In the power versus voltage curve of a PV panel, there exists a single maxima of power (peak power corresponding to a particular voltage and current). The efficiency of the solar PV panel is low at about 13%. Since the panel efficiency is low it is desirable to operate the panel at the maximum power point so that the maximum power can be delivered to the load under varying temperature and irradiation conditions. This maximized power helps to improve the use of the solar PV panel. A maximum power point tracker (MPPT) extracts maximum power from the PV panel and transfers that power to the load.

3.3 Battery storage and controller

Because of the intermittent solar irradiation characteristics, which highly influence the resulting energy production, the major aspects in the design of the PV systems are the reliable power supply of the consumer under varying atmospheric conditions. Therefore, a means of energy storage must be implemented in the design of a stand-alone solar system, and will be used to power the loads during night hours and cloudy days.

Cell batteries are currently the most used form of energy storage in the solar system. Lead acid batteries are the one considered in this paper as they are the cheapest and most popular.

When sizing a battery, two major parameters must be taken into consideration, the State of Charge (SOC) and the Depth of Discharge (DOD). The battery, with total nominal capacity C_n (Ah), is permitted to discharge up to a limit defined by the maximum permissible depth of discharge DOD (%), which is specified when designing the system. Koutroulis (*et. al.,* 2006) calculates the capacity of the battery at a point in time, t, as follows:

$$C_{(t)} = C_{(t-1)} + \eta_B (\frac{P_{B(t)}}{V_{BUS}})\Delta t \qquad (14)$$

Where $C_{(t)}$, $C_{(t-1)}$ is the available battery capacity (Ah) at hour t and t-1, respectively, η_B=80% is the battery round-trip efficiency during charging and η_B=100% during discharging, V_{BUS} is the DC bus voltage (V), $P_{B(t)}$ is the battery input/output power and Δt is the simulation time step, set to Δt=1h.

The size of battery storage can be calculated as follow (Zakaria *et al*, 2008):

$$Batterystorage = 2 \times AD \times TDWU \qquad (15)$$

Where:
TDWU is the daily-hours used;
AD is autonomy day ($1 \leq AD \leq 5$).

The controller is sized either with equation (16) or equation (17):

$$I = I_{sc}.F_{safe}. \qquad (16)$$

$$I = \frac{Cn}{t} \qquad (17)$$

Where:
I_{sc} is the PV short-circuit current;
F_{safe} is the safety factor;
C_n is the rated capacity of the battery;
t is the minimum amount of hours of operation.

3.4 Distribution system

Figure 5 shows the simplified distribution system of the DC microgrid system. The wire sizing has to comply with the South Africa National Standard (SANS) on the wiring of premises.

6 mm^2 for the generation and storage side, and 2.5 mm^2 for the distribution side will allow an acceptable tolerance of voltage drop for this low voltage system, refer to SANS 10142.

4. Simulation results

The BP solar BP3230T was selected based on the power demand and climatic conditions of the area retained for the simulation purpose. The BP3230 has 60 series connected polycrystalline silicon cells. The key specifications are shown in Table 3.

Table 3: Key specifications of the BP3230 solar module

Parameter	*Value*
Maximum power (P_{max})	230W
Voltage at P_{max} (V_{mpp})	21.1V
Current at P_{max} (I_{mpp})	7.90A
Short circuit (I_{sc})	8.40V
Open circuit Voltage (V_{oc})	36.7V
Temperature coefficient of I_{sc}	(0.065±0.015)%/C
Temperature coefficient of V_{oc}	-(0.36±0.5)%/C
NOCT	47±2°C

The 8A8DLTP-DEKA lead acid was selected as a means of energy storage. The key specifications are shown in Table 4.

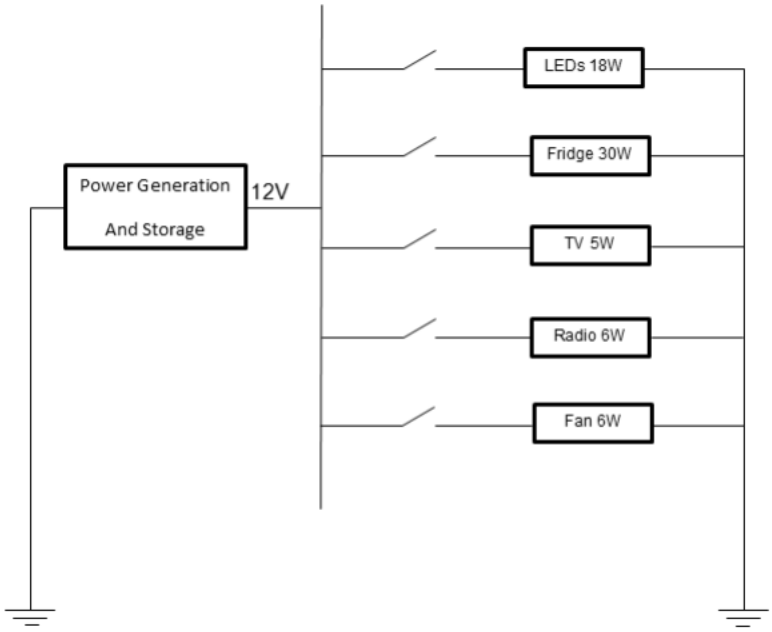

Figure 5: DC distribution system

Table 4: 8A8DLTP-DeKA key specifications

Parameter	*Value*
Nominal Voltage (V)	12V
Capacity at C/100	250Ah
Capacity at C/20	245Ah

To extract utmost power from the solar PV panel, the EPSOLAR tracer 2215RN has been selected as a MPPT solar charge controller. This MPPT solar charge controller has a peak conversion efficiency of 97% and a high tracking efficiency of 99%.

The climatic data of Mthatha in the Eastern Cape Province is used in this paper for simulation. The hourly temperature data was obtained from the South Africa Weather Service (SAWS) and the hourly solar irradiance data is provided by Helioclim through SoDa website. An extract of daily average of sun irradiance and temperature over a summer day and a winter day was used to simulate the power generated by the PV panel.

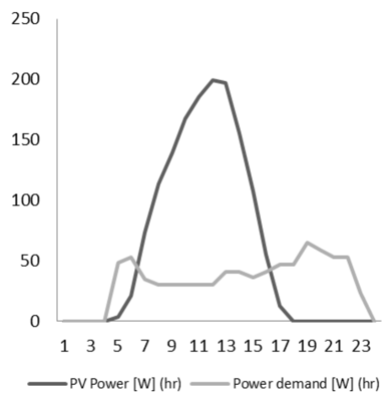

Figure 6: PV Power generation and power demand during summer day

The figures show the evolution of the power demand estimation and the power generated by the as well as the SOC of the battery. Figures 5 and 6 show the results of simulation during a summer day. Figures 8 and 9 show the simulation results during a winter day.

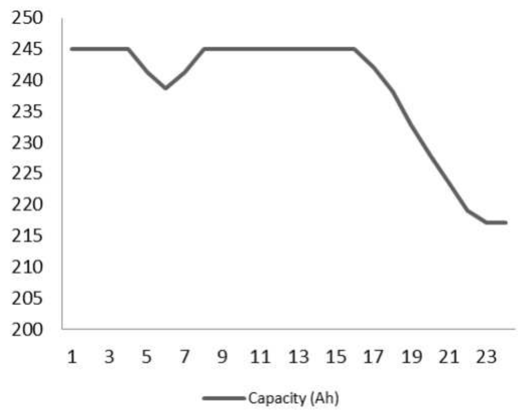

Figure 7: PV Battery charge and discharge during summer day

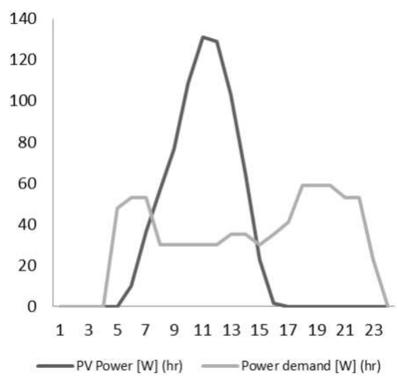

Figure 8: PV Power generation and power demand during winter day

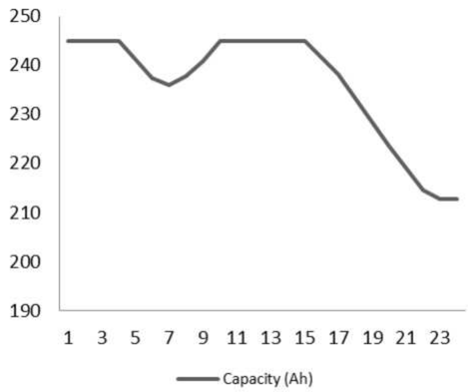

Figure 9: Battery charge and discharge during winter day

From the results of simulation, we can see that the PV panel can sustain the power demand, and the excess will be stored in the battery and will be used during no sunlight period. Also, the discharge of the battery is above the two set minimum SOC (40% and 50%).

5. Conclusion

The design of the low voltage DC microgrid system presented in this paper offers a simplified solar system as a means of power delivery to households in rural outlying areas. The importance and need for the use of renewable energy and cheaper technology in rural outlying areas were highlighted. A selection of energy efficient appliances based on the low-energy consumption restriction was presented. The proper sizing of the photovoltaic panel, the battery and the MPPT controller has been developed as well as the wires sizing. The simulations have been carried out and the results presented show the efficacy of the designed system. Further work could include a low-energy cooking device and more detailed modelling of the system components.

Acknowledgment

I would like to thank everyone who helped me with this project, friends and most of all to my supervisor Mr. Raji.

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Received; 8 October 2012; 12 May 2014

South African renewable energy investment barriers: An investor perspective

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Abstract

As recently as the year 2010, renewable energy contributed less than 1% of all the energy sources in South Africa. Possible reasons include the lack of private sector investment in Renewable Energy technologies. By way of a structured interview methodology, this paper explores the reasons why private investors are reluctant to invest in renewables. The responses point to political, economic, social and technological barriers limiting private investment in renewable energy. Other barriers that were identified include poverty, low levels of education, limited technological readiness and access to the electricity grid. Some of these barriers are specific to the South African context. The paper concludes that a closer relationship between government and the private sector is required to stimulate innovation in the renewable energy sector.

Keywords: renewable energy, financial investments, investment barriers, South Africa

1. Introduction

The South African government has articulated its short, medium and long-term vision for an environmentally sustainable, climate-change resilient, low-carbon economy and just society. The vision is outlined in the Cabinet endorsed National Strategy for Sustainable Development and Action Plan (2011-2014), New Growth Path (2010) and National Development Plan (2011). Several sector policies and strategies, including the Integrated Resource Plan for Electricity: 2010–2030 (2011), Industrial Policy Action Plan (2010), National Biodiversity Strategies and Action Plans and the National Climate Change Response White Paper (2012) also endorse this vision.

Relative to fossil fuel-based energy, renewable energy[1] (RE), has historically been expensive and still remains expensive for consumers (Pegels, 2010; Ogihara Gueye, King, & Mori, 2007). Limited innovation and investment in RE technologies is one of several reasons mentioned for the current high cost of RE prices (Pegels, 2010; Owen, 2006a). It has been shown that as a whole, the current level of global investment is substantially lower than that of countries like China, Japan and several other European countries (G20 Clean Energy Factbook, 2009). By analysing investment decisions in a typical RE project, this paper aims to identify the barriers to investment.

South Africa's position is unique, with a sophisticated financial system on the one hand, and very high income inequalities (a Gini coefficient of 53.8) on the other hand (UNDP, 2009; Sanders & Chopra, 2006). As such, South Africa is a good example of an emerging economy, the ideal context to base this study on. The study was confined to South African energy projects, and focused on factors that influence investment decisions, including investor background, the nature of the investor, and political, economic, social and technological factors during the period of 2009 till 2011. Previous studies focused on barriers to renewable technologies in a broader sense, dealing with the associated costs and challenges for each type of RE source (Painuly, 2001; Verbruggen, Fischedick, Moomaw, Weir, Nadai, Nilsson, & Sathaye, 2010).

2. Implications of the study

In brief, this research aims to explore the factors limiting investment in RE technologies in South Africa from 2009 until 2011. This study offers almost a historic view of RE investment prior to 2011 and it therefore does not consider any socioeconomic changes post the date of 2011. Private sector investment can be viewed as a necessary arsenal with the aim of making RE prices attractive compared with conventional energy prices. In order to understand why investment in RE is limited, it is important to understand the investment considerations of potential private investors. The findings could serve to inform the investment community about the importance of RE resources in the value chain, and the importance of promoting RE projects more aggressively. RE project shareholders could use the findings of this research to tailor their respective projects so as to secure adequate funding by making their projects more attractive for investment.

3. Literature review

3.1 Challenges of renewable energy

3.1.1 Political

Kebede *et al.* (2010) argue that the energy industry is one of the bases of any stable economy. This industry is therefore typically subjected to heavy political intervention by governments as a means of controlling volatility in the economy. Ahborg and Hammer (2012) as well as Krupa and Burch (2011) point to a lack of government support as one of the main barriers to the wider acceptance of RE. This confirms Martinot and Macdoom's (2000) view. These authors argue that apart from all of the other barriers that are hindering the wider acceptance of RE, the politics around the generation of RE is prime.

Mandle (2008) argues that politics, through state intervention, can substantially influence the ability to mitigate climate change resulting from conventional fossil-fuel technologies. As such, legislation and policies can be powerful state- driven tools with which to shape and steer an economy. These instruments cannot be separated from the politics of a country because states are inherently political institutions. It was over three decades ago that Weidenbaum (1983) made a recommendation that the state implements a more effective policy, where tax policies could provide tax breaks and reduce obstacles to certain types of energy projects that the state is trying to promote. More recently, Shoock (2007) advocates the use of legislation to stimulate both the demand and the supply side of the economy with regard to promoting cleaner and alternative energy sources. In support of Shoock (2007), both Kline (2010) and Tavallali (2010) argue that, in addition to better funding models, tax-based incentives could also provide funding assistance to RE projects. However, Verbruggen *et al.* (2009) have an opinion contrary to these. They argue that, generally, governments do not have the policies in place to support or promote RE technologies, as these technologies are relatively new. Winkler (2005) draws the debate to the South African context, by arguing that RE policy will be more effective if the current energy policy is improved. The lack of support and alignment policies means that RE technologies cannot be developed further, indeed, from a legal perspective, with no appropriate enforceable policies in place, RE technologies will not enjoy appropriate levels of funding or subsidies (Bode & Michaelowa, 2003).

It seems that the current policy set is not enough to unwed South Africa from its coal dependency (Oxford Analytica, 2009). For example, the approved amount of RE to be delivered for the feed-in tariffs needs to be clearly articulated in order to ensure diversity of supply. The latter is critical in order to assess the incremental upfront cost relative to the future environmental benefits. In contrast to South Africa, other developing countries such as China and South Korea, as well as developed countries such as Australia, Japan, the UK and the USA, have energy policies which provide attractive financial incentives to promote low-carbon electricity (Vivid Economics, 2010). Sebitosi and Pillay (2008) thereby note that while the rest of the world is experiencing tremendous growth in their respective RE industry, South Africa appears to have stagnated due to its misaligned environmental and energy policies.

3.1.2 Economic

One of the major factors making RE technology very attractive at the moment is the high price of conventional fossil fuel (Smith, 2007).

Rafaj and Kypreos (2007) calculated that if external costs, such as environmental and health damages were included in the price of electricity, non-fossil energy sources such as RE becomes more competitive. It can be argued that developing economies such as South Africa need cheaper energy prices to compete globally in order to secure their market share in energy dependant industries as well as to attract Foreign Direct Investment (FDI) (Doppegieter, Du Toit & Liebenberg, 1999). This cost bias means that RE technologies are expected to be less attractive locally than conventional fossil-fuel based energy (Kerr, 2010). According to statistics published by the EIA (2010), it is clear that South African energy resources are biased towards the conventional sources, as shown in Figure 1 (EIA, 2010).

Mathews *et al.* (2010) argue that RE projects can be made more economically viable by reducing their cost base. They point out that so far only public funding has been considered for RE projects, and without the private finance sector's involvement, RE will remain expensive. Prior to 2011, RE projects in South Africa were funded through carbon trading schemes which originated from developed economies. However, the prices of carbon generated through those schemes have been dwindling

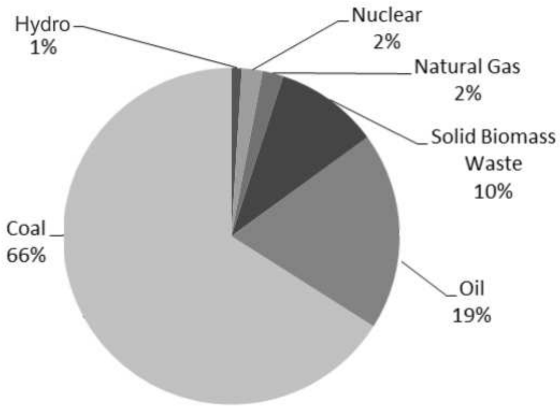

Figure 1: South Africa total primary energy supply by type estimates
Source: EIA (2010)

from some time now. Sebisoti and Pillay (2008) for instance provide the example of the Johannesburg Stock Exchange (JSE) that offers counters that trade in emission futures. These authors however point to a hindrance with this model in that it is intended to offset emissions from overseas industries. Moreover, experience illustrates that international CDM investors have a preference for destinations such as India, Mexico, and China. In his article, Owen (2006b) suggests that one of the ways in which to reduce the cost of production is by achieving economies of scale. However, this can only be done by means of widespread adoption of technology that translates into increased social acceptance.

The Kyoto Protocol, a legal platform for countries committed to reducing Green House Gases (GHG) emissions (UNFCCC, 1997) underwrites several objectives. In order to achieve these objectives, three main mechanisms were developed – Emission Trading (ET), Clean Development Mechanisms (CDM), and Joint implementation (JI) (Dutschke & Michaelowa, 1998). Certified Emission Reduction (CERs), Emission Reduction Units (ERUs), Voluntary Emission Reduction (VERs), EU-Allowances (EUAs) and Assigned Amount Units (AAUs) are the five main types of certificates generated from these mechanisms. Unfortunately, most of the CDM projects have been underperforming which actually results in minimal sustainable benefits (Schneider, 2007). The resulting CERs from these types of projects together with the low cost base could have a negative impact on emerging markets of emission credits by driving the CERs prices down through market saturation (Olsen, 2007). It is therefore argued that other higher local sustainable projects, such as RE projects, can be less favoured from an economic point of view (Sterk & Wittneben, 2005). Nussbaumer (2009) concludes that while the CERs cost will vary with the types and stage of projects considered they remain a pivotal means of reducing GHG emissions.

3.1.3 Social

Aside from economic and political matters, social dynamics play a role in RE uptake. The social acceptance of RE policy programmes and projects is particularly important. Wustenhagen, Wolsink & Burer (2006), identify three dimensions of social acceptance of RE Innovation: socio-political, community and market acceptance. They argue that both policies and technologies need to be adopted by society at large in order for an initiative to be successful. This is followed by community acceptance of decisions and RE projects by local stakeholders, residents and local authorities. Simon & Wustenhagen (2006) found that acceptance increases when stakeholders are directly involved with a specific type of RE project, such as wind farms. For example, according to Rogers (1995), market acceptance depends on the communication process between the potential adopting party and its environment, as this process facilitates the adoption of innovative technologies.

South Africa is in a very different situation from other developing countries, as the majority of the population cannot even afford basic cheap energy (Bennett, 2008). As a result, the social system is biased towards cheap and dirty sources of power (Lloyd, Cowan & Mohlakoana, 2004). In order to increase the adoption rate of RE sources, the country needs to first uplift its communities to the point where they can afford the basics, in order to then switch to RE sources (Bennett, 2008; Visagie & Prasad, 2006).

3.1.4 Technological

Fossil-fuel technologies have long been considered to be mature, but in most countries, they still attract substantial research and development funds to increase efficiencies, with the exception of a few countries such as Sweden, Spain, Switzerland and the United Kingdom (Schilling & Esmundo, 2009). Manne and Richels (2004) confirm that innovation can reduce RE production costs. Therefore, in order to make RE more competitive, technological innovations are necessary (Russell, 1999).

Painuly (2001) highlights other technological barriers such as a lack of standards, codes and certification and technical skills, lack of infrastructure such as the ability to link up to the grid, and a weak technological culture. Most importantly, lack of funding to sustain technological innovation is regarded as a limiting factor for cheaper renewable technology. In South Africa, some RE technologies have to be imported as they cannot be made more cheaply locally, for example solar panels, wind turbine blades and Concentrated Solar Power (CSP) equipment (Bennett, 2008).

The nature and maturity of RE technology also influences any investment decision. Accordingly, a mature and established technology such as solar photovoltaic (PV) energy will attract more funding than any other type of RE technology (Jacobsson & Bergek, 2004). The post 2011 RE landscape in South Africa through the roll out of the Renewable Energy Independent Power Producer Programme (REIPPP) proves this point since most of the solar farms generate CSP, which feeds into the national grid.

3.2 Factors influencing investment in renewable energy

3.2.1 Political

Tyner (2007) argues that since the US government subsidised ethanol in 1978, the ethanol industry has experienced substantial growth. This subsidy was in line with the government's mandate to support the farming industry, environmental concerns and energy security. Tyner (2007) argues that the success of this industry resulted from state intervention, enabling its growth. Karagöz (2010) points out that private investors are particularly sensitive to political risks, which include political stability and the stability of policy implementation; this sensitivity can be extended to the facilitation of infrastructure (Karagöz, 2010). It can therefore be argued that investment decisions can be influenced by political factors.

3.2.2 Economic

Bennett (2008) argues that due to limited local manufacturing capability (infrastructure, patents and innovation of RE technologies), most of the RE technologies used in South Africa are imported. It follows that any investment in these types of projects will be subject to foreign exchange exposure. This exposure increases the risk profile of the investment because for a higher risk portfolio investors expect a higher return, this can make some RE projects unviable (Shefrin, 2001). The South Africa Rand has a history of intense fluctuations.

3.2.3 Social

It is argued that volatility is also a deterrent to investment (McDermott & Tavares, 2008). Over the last decade, the world has experienced substantial fluctuations in crude oil prices, as shown in Figure 2. Accordingly, as the price of oil rises, RE investments become more attractive. Similarly, as the price decreases, RE investments become less attractive (Wakeford, 2006). It has been proposed that price volatility could be mitigated through government intervention, by diversifying the energy portfolio to include RE (Janczura, 2010).

3.2.4 Technology

From an investment perspective, RE technologies are relatively new while some technologies, like wind and PV solar power, are more established, others, such as geothermal and solar CSP, are still in their infancy (Sorensen, 1991; Visagie & Prasad, 2006). Generally, investors consider the respective maturity levels of the RE technology in their investment decisions.

3.3 Conclusion

The arguments presented confirm that RE adoption is influenced by political, economic, social and technological factors. It was therefore considered important to explore these factors in order to understand the prevailing industry situation.

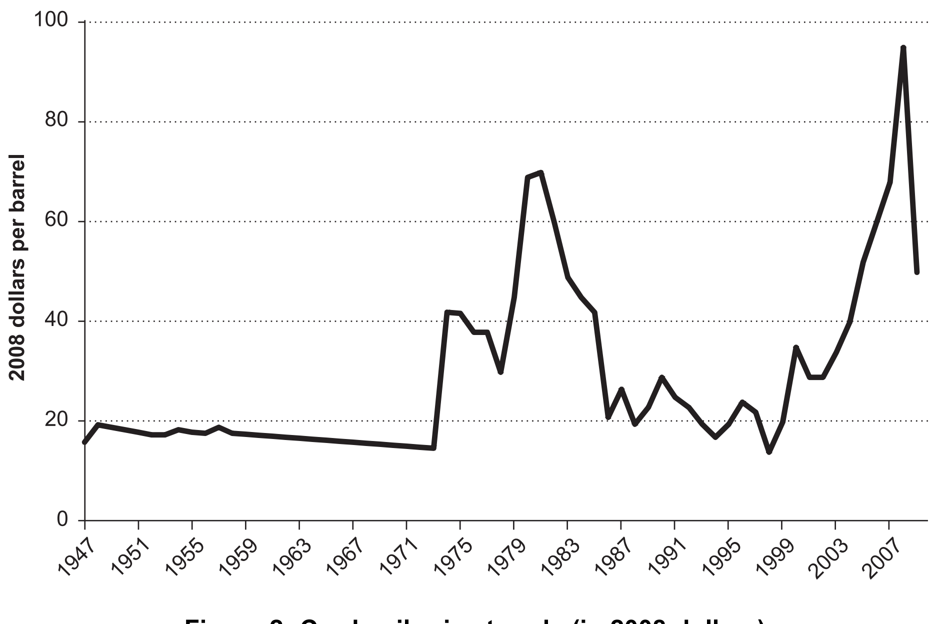

Figure 2: Crude oil price trends (in 2008 dollars)
Source: Williams (2009)

4. Research methodology

While there have been many studies dealing with the barriers to the adoption or penetration of RE globally, there was a paucity in literature specific to South Africa and its unique barriers available from South African academic databases. Literature addressing investment in RE in South Africa, with a focus on investment from the investor's perspective, was even scarcer.

This may be attributed to the fact that the RE industry in South Africa is a relatively new field. As this is an emerging field of interest, an exploratory survey-based research design was considered to be the most appropriate method to use (Zikmund, 2003:54). Pragmatic researchers need to appreciate and use both qualitative and quantitative methods in their research (Onwuegbuzie & Leech, 2005). This research design therefore included the use of both quantitative and qualitative research methods. Since this research was designed to gather data at a specified point in time, it is categorised as a cross-sectional study. The unit of analysis was the financial investment decision made by investors when investing in RE technologies.

In order to achieve its objectives, this research was broken down into three phases: Phase One identified potential factors which investors considered during their RE investment decision. Phase Two tested whether these factors were in fact considered by South African RE investors when making investment decisions. The research and interview questions are included in Appendix A. The final phase of this research comprised the data analysis.

The sample consisted of 16 South African based companies, which covered each segment of the investment community so that it would be representative of the general population of relevance. These investment companies are shareholders in various energy projects in South Africa. Part of their finance portfolio includes RE Projects. The selection was through convenience sampling, as the number of respondents available was limited. These included financial and other types of institutions that invest in RE technologies. A total of 10 companies agreed to take part in the survey, resulting in a response rate of 62.5 per cent. The companies were represented by individuals who make or contribute to the investment decisions into energy projects.

Owing to time constraints and limited sample availability, an adapted cognitive interview technique was chosen (Beatty & Willis, 2007). It was adapted in the sense that the structured questionnaire was answered by the respondent during the interview. The interviews were conducted by the researcher in person. This methodology provided the researcher with the opportunity to explore further, insights raised in the response. With a generic, distributed, self-administered questionnaire, qualitative responses can sometimes be incomplete or misunderstood and therefore misinterpreted, which can influence the data analysis and may skew results.

Since data consistency allows responses to be analysed appropriately, therefore a structured questionnaire was used and the same set of questions was presented to each respondent. The questionnaire was designed in such a way that the responses were automatically categorised into the six predefined sections, namely Introduction, Political, Economic, Socio-cultural, Technological and General. It also contained an open-ended section in which the respondents could make additional con-

Table 1: Sample

Category	*Number (count)*	*Percentage*
Sample size – Number of companies identified	16	100
Number of companies providing its services to the financial industry	13	87
Number of companies providing its services to the energy industry	3	13
Number of companies with their head office located in Gauteng, South Africa	16	100

Table 2: Sample surveyed

Category	*Number (count)*	*Percentage*
Sample size – Number of companies who responded	10	100
Total number of respondents interviewed	10	62.5
Number of respondent per company	1	
Number of companies providing its services to the financial industry	8	80
Number of companies providing its services to the energy industry	2	20
Number of companies with their head office located in Gauteng, South Africa	15	100
Number of respondent with financial (business) background	7	70
Number of respondent with technical (engineering) background	4	40

tributions to any section of the questionnaire. The Questions contained in the questionnaire were mostly closed and required short narrative responses. Some questions in the respective sections required the respondent to select an appropriate response from several alternative statements. If the response was vague or inadequate in terms of richness, then a follow-up question was asked. This method ensured that the required narrative response was of sufficient relevance and substance to be used in the analysis. A consent form was included in the first section of the questionnaire.

A preamble and background information about the research was sent to the respondent a few days before the actual interview session. Interview questions themselves were not sent to the respondent prior to the interview session, in order to prevent any response bias. The interviews were conducted by the researcher and captured in an audio format with prior permission from the respondent. A hard copy of the questionnaire was used to record important response aspects. All audio recordings were critically reviewed to confirm and highlight key insights, which the researcher might have overlooked during the interview.

The primary data obtained from the questionnaire was both quantitative and qualitative in nature. A frequency analysis method was used to analyse the quantitative data, while narrative content analysis was used to analyse the qualitative data. Microsoft Excel and NCSS software packages were used to conduct the frequency analysis. The first step in the narrative content analysis was to group the narrative responses to the same question from each respondent on one page. The responses were then categorised under different headings after which, similarities, differences and new insights were noted (Saunders, Lewis & Thornhill, 2003). These were analysed in relation to the literature review conducted and the pertinent factors limiting investments in RE technologies.

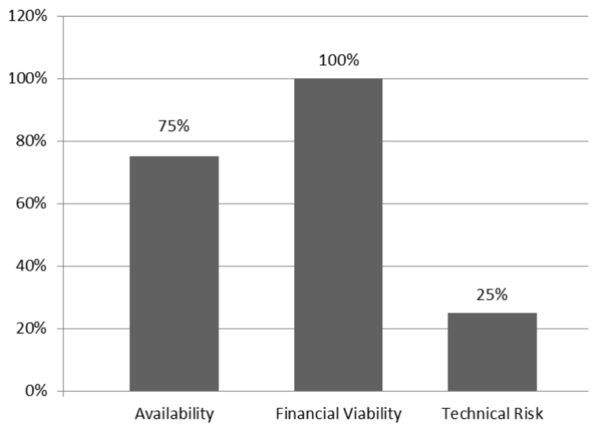

Figure 3: RE selection criteria

5. Discussion of results

5.1 Financial viability

The financial viability of the respective potential projects was mentioned by 60% of respondents. Investors were very concerned about the financial viability of their investments and factors such as high capital costs, the price of products, tax benefits, grants, subsidies and means of raising capital through debt and equity were mentioned as being prime considerations when making investments. Simply put, investors will not invest in any type of technology if it is not financially viable. Financial viability related to a number of factors mentioned by the respondents, such as capital, operational costs, market, selling price and foreign currency risks. This is illustrated in Figure 3.

It can therefore be argued that until the cost of RE technologies can compete with traditional fossil based technologies, investment in RE will remain lower than investments in fossil fuel based technologies. In order to address this imbalance, competitiveness level of RE technologies may be improved through political interventions through its policies as recommended by Martinot and Macdoom's (2000) as well as Jacobsson and Lauber (2006). It follows that if the political climate, objectives and instruments, such policies and tax breaks, are aligned with the promotion of RE based technologies, then the cost of RE technologies will be able to compete with traditional fossil based technologies.

5.2 Need for clarity

One of the areas the research attempted to establish was the nature of political influence on RE investment decisions. The respondents were asked if the current South African political climate was conducive to RE investment. The responses are documented in Figure 4 and show that investors did not believe that the political climate was conducive to substantial investment in this industry. The reasons are a lack of clear regulations and government support, a preference for conventional fossil-fuel based energy, and the use of political forces to shape the energy industry with the government's own monopoly. Responses to some of the questions were extremely divided, rendering inconclusive results. One such question was on whether the current set of regulations and incentives were sufficient to promote or hinder RE investments. However, some themes kept reappearing, such as the need for clarity on the prevailing set of incentives and regulations.

The respondents were of the opinion that the South African government was currently unsure of its course of action. They demonstrated this point by noting the inconsistent policies and initiatives, such as those involving the RE Feed In Tariff System (REFIT) system. The latter is a mechanism to pro-

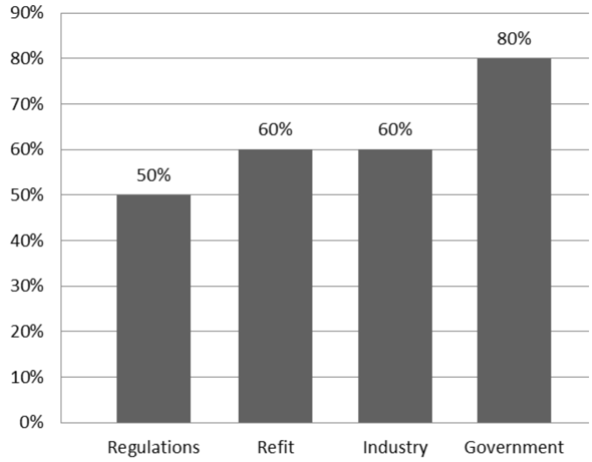

Figure 4: Political influence reasons

mote the deployment of RE and places an obligation on specific entities to purchase the output from qualifying RE generators at pre-determined prices. The REFIT Guideline document made references to platforms that have not yet been finalised or endorsed, such as the Independent Power Producers (IPP) and the Integrated Resource Plan (IRP) (NERSA, 2009). According to REFIT, the financial capital requirements for joining the grid with any type of RE are substantial. This automatically limits investors in their decisions. As of August 2013, a Renewable Energy Independent Power Producer Program (REIPPP) has since been approved and is currently operational. Three rounds of bidding have taken place under the auspices of this program with the first round already having generators on line (Kane and Shiao, 2013).

The need for clarity therefore suggests that until there is alignment of the political objective and its various instruments, investment in RE technologies will remain lower than fossil-fuel based technologies. Furthermore, investment in RE technologies will remain financially unviable, supporting the previous finding, which asserts that the political climate needs to be conducive by making its policies and goals clear.

5.3 South African barriers

This section unpacks the barriers to RE investment specific to South Africa and goes beyond the financial, political, social, technological and economic aspects. The results obtained mentioned three key challenges for South Africa in this area namely: poverty and inadequacies regarding grid access, education and technology. These were believed to be hindering the adoption of and investment in RE technologies. In a developing country, these barriers are to be expected; however, it was perceived that South Africa in particular had tougher challenges than other developing countries.

5.3.1 Poverty in South Africa

The 2012 report titled: 'Monitoring the changing face of South Africa's poverty,' illustrates that the poverty is still a harsh reality for large numbers of people. The figures are measured according to the poverty line adopted by the government of US2 per day or below.

Based on this, it could be seen that poverty is indeed a challenge for South Africa. With the prevailing levels of poverty, it can be understood why the market for RE, a more expensive alternative to electricity is not large. Respondents confirmed that with the high levels of poverty in South Africa, for domestic purposes, cheaper alternatives such as paraffin will always be the default choice making RE even less attractive. Stats SA (2013) showed that 12.6% of South Africans mainly in rural provinces still use wood for cooking. This barrier to RE adoption was confirmed by the sample surveyed.

5.3.1 Insufficient grid access

Despite the fact that South Africa had 85.3% electrification in 2011, approximately 15% of the population still did not have access to electricity through the grid (Stats SA, 2013). It can be concluded that a large area of the country remains detached from the grid. If RE feeds into the grid, generating more power, the social impacts will not be felt by those

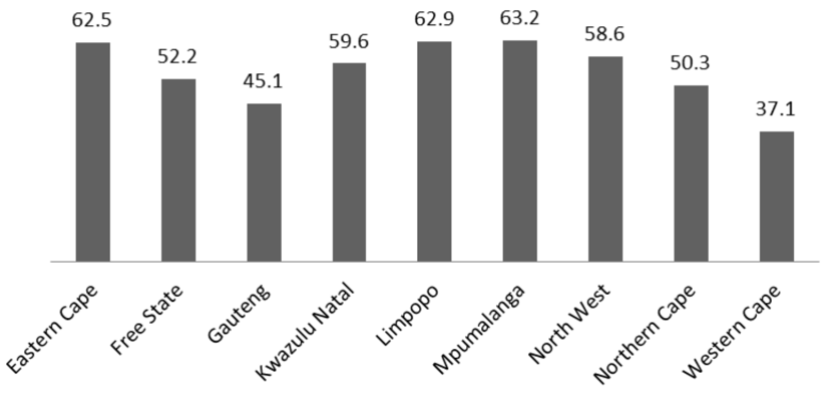

Figure 5: Poverty indicators by province
Source: Schwabe (2012)

who need electrification. Therefore, the statement made by respondents that access to the grid was a problem is justified and it can be concluded that access to the grid has an influence on the social component of RE investment.

5.3.2 Inadequacies in education

One of the most serious challenges facing South Africa is education. According to the Global Competitiveness Report 2010/2011, released by the World Economic Forum, South Africa ranked 129th for primary education and 75th for secondary education out of 139 countries in 2009 (Schwab, 2010). Approximately 24% of children are in the wrong grade for their age and 6% are not in school (Barnes, Wright, Noble & Dawes 2007). However, in 2008 that number decreased slightly to 34. 3% or a figure of 6. 8 million (Hall, 2010). With this number of citizens lacking basic education, it was not surprising to find that investors were nervous about the low social acceptance of a new technology, especially at domestic level.

In order for society to adapt to RE and technology, people must be able to comprehend its benefits, which requires sufficient education to understand and appreciate the possibly disastrous consequences of current energy use. Referring to the 2007 European Conference on Local Energy, Sebitosi and Pillay (2008) highlight that traditional school curricula often do not offer the flexibility to integrate such subjects in teaching. Whilst industry experts do exist, these persons often lack access to schools where they can offer their knowledge and information which in turn can impact the skills force and innovation base for the future. As mentioned in the foregoing, the majority of the RE technology in South Africa in imported. This point supports the proceeding factor about challenges in technology.

5.3.3 Challenges in technology

According to the Global Competitiveness Report 2010/2011 released by the World Economic Forum, South Africa ranked 76th in technological readiness out of 139 countries in 2009 (Schwab, 2010). It is clear from the results of this study (which are shown in Figure 6) that there is a correlation between the RE investment decisions and technological factors. Many of those countries ranked higher than South Africa are ahead in RE technology investments, innovation and policy. A major factor highlighted by respondents was the use of technologies developed and produced outside South Africa. While some might believe that these technologies are unsuitable for the local market, it would be difficult to overlook these technologies entirely, as most of them have already been developed and tested. It would be easier for South Africa to adapt itself to suit the technology, rather than the other way around.

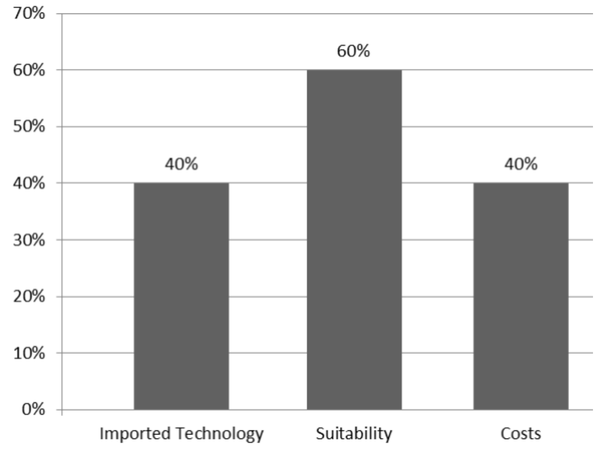

Figure 6: Technology influence reasons

5.3.4 Other barriers

From the responses to the open ended questions, two non-classified issues were raised namely, quality of labour force and infrastructure. Since RE is a relatively new field in South Africa, skills will definitely be a challenge. With the limited human capital that South Africa possesses, it will be difficult to find qualified and experienced skilled labour to service the industry.

South Africa has one of the best developed infrastructure systems on the African continent yet the major relevant infrastructure related constraint that remains is access to the grid. Whilst infrastructure, including roads, ports and a well-established railway system, provides South Africa with an unquantifiable advantage, in terms of RE investments, this bears little mileage

6. Conclusions

This study was undertaken to investigate the factors limiting financial investment in RE technologies from an investor's perspective (Ghoorah, 2010). Consequently, a survey was conducted using exploratory interviews, which revealed that five aspects mainly influenced RE investment decisions, namely investor background, political factors, economic factors, social factors, and technological factors. However, it was found that, despite the influence of all the other factors investigated, the financial viability of the potential project was the most important criterion that investors considered when making investment decisions. The other major finding was that the majority of the organisations aimed at optimising return on investment.

Politically, it was clear that South African RE investment decisions were affected by political and legal frameworks, as stated by Martinot and Macdoom (2000), Painuly (2001) and Krupa and Burch (2011). Prior to 2010, the South African political environment was not conducive for optimising such investment. The absence of clear objectives, lack of alignment of state substructures and lack of government support were the major reasons given for this situation, which are in line with the findings of Robert & Weightman (1994) and Mandle (2008).

Findings showed that South African RE investment decisions were influenced by economic factors, as stated by Martinot & Macdoom (2000). These factors mainly consisted of demand and supply, foreign exchange and access to capital. With the price of electricity being controlled and capped, it was difficult for any investors to influence and manage a return on their investment. Since most of the RE technologies were imported, projects that needed capital to bring in these technologies were exposed to foreign currency risks despite investors expecting guaranteed returns. In addition, raising capital in this economy is another constraint, as the amount of capital needed is substantially higher than that for conventional energy projects. Prior to 2010, there were very few incentives for investors to raise capital for this type of project.

The lack of social awareness was a major stumbling block for investors, as it limited the RE technology adoption rate, which in turn, limited the RE market. It was found that, according to investors, South African society is not aware of the current environmental issues, the need for RE technologies and alternatives available to them; this is in line with the findings by Simon & Wustenhagen (2006). Other constraints mentioned included the poverty, lack of grid access, and lack of education in South Africa (Bennett, 2008).

It was also found that most RE technologies were imported into South Africa, as the country does not produce its own technology. The positive result is the adoption of international standards, for example ISO 50001, 23045, 13790, 81400, and certification, for example, ISO/IEC 17020, that accompany these imported technologies. Owing to the fact that the South African RE industry is in its infancy, relevant skills and expertise are scarce, despite advanced infrastructure. RE related infrastructure, such as access to the electricity grid, needs to be improved to enable growth in the RE industry.

The need for clarity on the prevailing set of incentives and regulations was a major topic that was identified. Investors were of the opinion that the South African government was currently unsure of its course of action. They demonstrated this point by noting the inconsistent South African RE policies and initiatives.

From an organisational perspective, almost all investment companies allocate their resources strategically in order to optimise their returns. This was proved to be the case in this study, where all the organisations surveyed had a mandate to maximise their returns in different ways (Shefrin, 2005; Tetlock & Mellers, 2002).

As with all research, there were some limitations of the study that point to suggestions for future studies. With regard to the research methodology, among the most common errors was non-response bias (which is normally caused by respondents choosing not to respond to some questions for personal, sensitivity or other reasons). Then there was response bias (where the response is influenced by the respondent's perception of what the researcher wants to hear). There could also be extremity bias, whereby respondents exaggerate issues by responding at the extreme end of the scale to highlight certain issues. In addition, there may be interviewer bias, in which the interviewer may lead respondents to make responses which they would not normally have given, or influence the response obtained.

Although it would have been interesting to compare the findings of this study with those of the rest of the Brazil, South Africa, India and China (BASIC) countries, this fell outside its scope. Such a comparison would be useful, as each country could use the findings as a point of reference to improve their investment profile. This is an opportunity for future research. Other avenues also include the study of potential factors, which could prove to be important in affecting investment decisions in the RE field. A study of various initiatives, such as a 'greenbond', REFIT, IPP, Tradable Renewable Energy Certificates (TREC) and their effectiveness in promoting RE could also be useful.

Notes

1. The Integrated Resource Plan: 2010–2030 (2011) provides for the disaggregation of renewable energy technologies to explicitly display solar photovoltaic (PV), concentrated solar power (CSP) and wind options.

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Received 19 September 2013; revised 15 May 2014

Appendix A

Q. no	*Category*	*Research questions*
1	Investor	Are renewable energy investment decisions influenced by investors' qualifications and experience?
2	Political	Are renewable energy investment decisions currently influenced by political/legal frameworks in S. Africa?
3	Political	How do the South African political/legal frameworks influence renewable energy investment decisions?
4	Economic	Are renewable energy investment decisions in South Africa influenced by the prevailing economic factors?
5	Economic	How do the prevailing South African economic factors influence investment in renewable energy?
6	Social	Are renewable energy investment decisions in South Africa influenced by social and cultural factors?
7	Social	How do the South African social and cultural factors influence investment decisions in renewable energy?
8	Technology	Are renewable energy investment decisions in South Africa influenced by technology factors?
9	Technology	How do technology factors influence investment decisions in renewable energy?
10	Organisation	Do internal company processes influence renewable energy investment decisions in South Africa?
11	Organisation	How do internal company processes influence renewable energy investment in South Africa?

Appendix B

Q no.	*Category*	*Questions*	*Response choices*
1	Investor	Background	• Financial • Engineering • Social Science • Other
2	Investor	What is your highest qualification?	
3	Investor	What did you major in?	
4	Investor	If all things were equal and you had to choose one project for investment, which type of RE project would you invest in? Please explain reason for this choice?	• Solar • Hydro • Wind • Bio Mass • Geothermal
5	Political	Are renewable energy investment decisions currently influenced by political/legal frameworks in South Africa?	• Yes • No
6	Political	Based on your experience, how would you describe the current role of the state in the RE industry?	• Yes • No
7	Political	Please indicate the importance of the role the state should have with respect to RE investments?	• High • Medium • Low
8	Political	Do you think the current government incentives & regulations are enough and in favour of promoting investments in RE industry? Why?	• Yes • No
9	Economic	Are renewable energy investment decisions in South Africa influenced by the prevailing economic factors?	• Yes • No
10	Economic	Does the selling price of RE influence your RE investment decision?	• Yes • No

11	Economic	How do you rate the financial investment involved in a RE project relative to a conventional energy project in SA? Is it:	• More costly & longer life cycle • Less costly & shorter life cycle • The same
12	Economic	How do you economically differentiate between RE projects and conventional energy project?	• Margin • Project life cycle • Associated financial risk • All of the above
13	Economic	Do you cater for the long term associated cost to ensure sustainability?	• Yes • No
14	Economic	Which of the following economic factors affect your investment decisions with special focus on RE the most? Why?	• Financial eg interest rate • Macro-economic e. g. foreign exchange • Micro economic e.g. market share • All of the above
15	Social	Are renewable energy investment decisions in South Africa influenced by social and cultural factors?	• Yes • No
16	Social	If yes, how do you communicate with the society concerned?	• Frequently a) In person • Occasionally b) Intermediate
17	Social	If yes, would you like the community to participate in the RE project?	• Yes • No
18	Social	Do you think that poverty in SA influences the adoption of RE which in turn influences your investment decision?	• Yes • No
19	Social	In your opinion, how important is the needs of the particular society when considering an investment in an RE project affecting that particular society?	• Yes • No
20	Social	In your opinion, how important is the needs of the particular society when considering an investment in an RE project affecting that particular society?	• Very important • Moderately important • Not important
21	Social	If your answer to question 4. 6 is either a or b then how would you integrate the social component into the RE investment decision?	• Yes • No
22	Social	How would you describe the social acceptance of RE technologies in SA compared to the rest of the world?	• More • Same • Less
23	Social	In your opinion, what should be done differently to promote further social acceptance of RE technologies in SA?	• Yes • No
24	Technology	Are renewable energy investment decisions in South Africa influenced by technology factors?	• Yes • No
25	Technology	Do you finance technological innovation in RE?	• Yes • No
26	Technology	How does the development stage of the technology involved in a RE project influence your investment decision?	• Yes • No
27	Technology	In your opinion, how does the RE technology in SA compares to international in terms of the following: • Standards • Certification • Skills requirements • Infrastructure	• Open ended
28	General	Does the company have an investment policy?	• Yes • No
29	General	Is it enforced?	• Always • Sometimes • Never
30	General	Does the shareholders have any influence in the RE investment decision making process?	• Yes • No
31	General	Does your organisation differentiate between financing a conventional energy technology versus a RE technology? If yes how?	• Yes • No
32	General	Based on your experience and given the challenges that SA is facing currently, select two of the most important aspects discussed above (i. e. Political, Economic, Social and technological).	• Political • Economic • Social • Technological
33	General	Considering these two aspects chosen above, describe what would you change or add in order to improve the level of investment in RE technologies in South Africa?	• Open ended

A PV power supply module for a portable Cubesat satellite ground station

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Abstract
This research focuses on the problem of powering a remote and mobile satellite ground station, where utility power is unavailable. It focuses on the use of photovoltaic energy, which is now widely accepted as an alternative source of energy. However, PV suffers from low conversion efficiency, non-linear I-V characteristics, which depend on temperature changes and the earth rotation. The research focuses on accurate determination of the ground station power budget whose total power demand involves an azimuth and rotator function and a current which varies depending on the stages of communication with the satellite. The power budget is used to determine the size, the ratings of solar generators, batteries and the system components. With the aid of a power logger, the PV voltage, the battery voltage, the AC voltage and PV power output is analysed for varying satellite loads. The data is analysed by taking into account the solar irradiation level on the day of measurement and the percentage cloud cover. This method is found to improve the reliability and can be adopted to improve reliability of standalone PV systems. The results are vital in PV power management and design.

Keywords: PV standalone power system, CubeSat satellite ground station, solar generator

1. Introduction

The mobile satellite ground station is essential with the increased use of satellite technology for communication, education and for the radio amateur enthusiast. There is a need to extend this technology to the remotest parts of Africa, but many of these areas lack a connection to the electrical grid. This research is an attempt to solve this problem by developing a PV standalone module ideal for a portable satellite ground station.

Kaldelis et al., (2010) observe that 90% of today's installed PV power is standalone with 80% being used in communication and water pumping and, while the initial cost of a PV array is higher than a diesel generator, it is maintenance free, has no fuel cost, no replacement of parts, and lasts up to 20 years. While the diesel generator lasts for only 10 years. They conclude that PV standalone with a battery is efficient up to 1kW load. This makes it ideal for the ground station application since its demand is about 600W. The research addresses lack of reliability of the systems due to poor sizing of the components. A larger solar panel than the battery will result in wastage of power as heat and an unnecessarily high cost of the energy produced, while a smaller panel makes the installation unreliable. The research attempts to use the power demand of the load, to come up with equivalent size of panels, components and battery to design a reliable and portable PV standalone system.

1.1 South Africa PV power production outlook

The PV industry scenario in the world is as follows: The USA completed a 14MW plant in 2007 and Spain a 20MW plant in the same year. The scenario in Africa is different with its PV systems being mostly standalone systems, having a production capacity of less than 1MW. This finds application in rural electrification, health centres, and rural households. The same scenario is replicated in Bangladesh, Kenya, and Sri-Lanka. South Africa has this form of PV system with an estimated capacity of 21MW. Bhandari and Stadler (2011) observe that, there has been a rapid growth in production of low cost photovoltaic components. This coupled with steps taken by some governments to subsidise the cost of PV installation and the initiative by some countries to purchase PV energy connected to the grid has made photovoltaic energy economically viable.

South Africa is credited with having some of the highest amount of irradiation globally with Northern Cape Province having the highest solar resource in the country. It has 30% higher irradiation levels than the best sites in Spain. Upington in the Northern Cape has more than 6.5kW/m^2/day average global irradiation. Other areas include the Free State, North West, Limpopo, and interior parts of Western Cape and the Eastern Cape. Thus solar potential in South Africa is considerable.

The South African Department of Energy conducted a pre-feasibility study, through an MOU between the government and the Clinton Climatic Initiative in October 2009, with the aim of exploring the potential of a solar park. This study recommended one of the potential sites as Upington in the Northern Cape. This proposed site has the potential of producing up to 5000MW of electrical power.

1.2 Load capability of PV standalone system

Kaldelis *et al*, (2010) states that there will be a drastic increase in the market of a PV standalone system in developing countries in future, especially in rural electrification. They note the following trend:

- Currently it can be estimated that 90% of today's installed PV power is stand alone.
- Up until 1997, about 640MWp of PV power had been installed.
- 80% of all PV stand-alone power installed is used in communication, water pumping and domestic power supply.

The German Solar Energy Society, Ecofys (2005), notes the following economic considerations in deciding on a power system:

- *Portable throw away batteries:* There will always be a market for portable primary throw away batteries for the lowest levels of energy demands e.g. watches, torches and radios. Good rechargeable batteries with a PV battery charger will prove cheaper than disposable batteries over a few years.
- *Domestic power supplies:* For on-off domestic supplies for lighting, TV, fans etc., a battery based supply charged by a PV or wind is likely to be the most cost effective. If occasional power peaks occur, a backup generator can be considered.
- *A small village or a number of domestic supplies:* The economic choice is either individual based battery units (solar home systems or commercial battery charging) or a centralised scheme made up of a PV plant, diesel generator or micro-hydro.
- *Remote water pumping:* The economic choice can be a PV system, wind pump or diesel.
- *A large village:* Where a hundred of kW is required. The economic choice is between micro-hydro, diesel or extending the grid.

From this analysis it can be concluded that the most economic load of a PV system is limited by the size of the load to be powered.

2. Challenges of PV implementation

The most commonly used solar cells currently have a light to electricity conversion efficiency of only 16%. This poses a challenge to this research as the CubeSat Satellite Ground Station load is variable and needs quite large power during tracking and downloading of data within a specified time limit. This presents a challenge in accurate determination of the power budget of the ground station and the rating of the solar generator capable of providing this power.

2.1 Effect of solar insolation

The amount of sunshine received at any time during the day is called solar irradiance, light intensity, solar flux, solar intensity, solar irradiance or irradiation. Solar irradiance varies throughout the day due to the movement of the sun and the clouds. The amount of irradiance measured in a day over a period of time is called daily solar insolation. Its units are watts per square meter (W/m^2) or milliwatts per square centimetre (mW/cm^2). On a very clear day, the irradiance reaching a surface that faces the sun is approximately equal to 1000W/m^2. This is also represented by light spectral AM1.5 (Robert, 1991). As solar irradiance plays a vital role in the output power of the PV system, but how will the solar insolation level affect the operation of the designed system? What level of insolation results in efficient operation? How will the system operate in other insolation levels?

2.2 Temperature effects

Temperature rise and fall has a significant effect on the PV output. A rise in temperature reduces the performance of the array. Drop in temperature increases the voltage output. The temperature of the site of operation is taken into account.

2.3 Insolation and current effect on the system

The electrical current generated by a module is directly proportional to the irradiance reaching it. This means for maximum current output, the sun should be overhead the module and the module should be placed horizontally. If the position of the sun in the sky is about 30 degrees, the module should be tilted at an angle of 60 degrees from the horizontal for maximum current. As the sun moves irradiance changes thus the generated current varies throughout the day. The charging current is highest at midday and lowest in the evening. This means highest charging of the battery happens in the middle of the day. Clouds cover affects the irradiance and the charging current. During cloudy days, little current is generated as the irradiance reaching the earth is reduced. When there is a thin layer of cloud the irradiance might be 300W/m^2, with thick cloud cover this is reduced to 100W/m^2 and the current will be zero with very little charging (Robert, 1991). The challenge is to determine the effect of the sun movement and the percentage cloud cover on the designed PV system.

2.4 PV components power rating effect

A photovoltaic system consists of PV components sized and connected to work in harmony. The components making up a PV system are:

- A solar generator with a mechanical support
- Storage (batteries)
- Power conditioning, and control equipment

PV systems rely on the irradiation of the solar energy on the PV cell to generate electricity. Without this irradiation, no energy is generated. To allow for continual supply of energy to the loads at night and during cloudy seasons, energy is stored. A battery is used for this purpose. Other elements used with PV systems include:

- Power conditioning elements; these are used to condition the DC voltage from the solar cell to AC.
- A PV system depends on irradiation, which is very variable. The control equipment boosts the solar energy and reduces this variation. They interface different parts of the system to the DC load.

In order to increase the reliability of the system, there is a need to design size and carry out proper installation and termination. Markvat (2008) observes that reliability of solar energy plays a crucial part in its design. Most decisions during design consider maximum power production and reliability.

The challenge for this project is to determine the CubeSat ground station power budget, followed by the determination of the rating of the solar panels and the PV components capable of carrying this load, taking into consideration the cost of the PV energy produced.

3. Methodology

3.1 The satellite ground station load

Figure 1 shows the satellite ground station equipments. The azimuth/rotator is powered from 227VAC. It's used during tracking and downloading data. The communication equipment includes the transceiver, RF line control unit, receiver and the microphones. These are powered from a 13.8VDC, 0-30A power supply. The PC is powered from 227VAC. Figure 2 indicates the antennas at the CPUT satellite ground station use during tracking and downloading of data. This is the overall load to be powered by the PV power module.

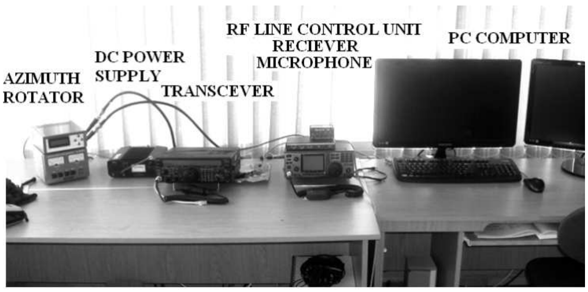

Figure 1: Ground station equipment

Figure 2: Antennae for satellite tracking

3.2 Ground station power consumption determination

3.2.1 Azimuth/ rotator maximum power

The power consumption of the azimuth/rotator is determined by logging the power while operating it up to its full operation capacity, when both Azimuth and controller functions are at maximum. Table 1 shows the maximum current and power measurements.

Table 1: Azimuth/Rotator power measurement

Time of day	*Elapsed*	*Voltage (V)*	*Current (A)*	*Power (W)*
11:44:16	0.02	227	5.51	9.82
11:44:21	0.02	227	5.52	9.93
11:44:26	0.02	227	0.00	8.31
11:44:31	0.02	227	5.50	9.93
11:44:36	0.02	227	5.54	9.93
11:44:41	0.02	227	5.56	100
11:44:46	0.02	227	5.57	101
11:44:51	0.02	227	5.60	100
11:44:56	0.02	227	5.63	102

3.2.2 Communication equipment power

Table 2 shows the variation of the current, voltage and the resultant power output during tracking and downloading of data from a satellite.

Table 2: Power output of communication function

Current (A)	*Voltage (V)*	*Power (W)*
0	13.8	0
5	13.8	69W
10	13.8	138W
15	13.8	207W
20	13.8	276W
25	13.8	345W
30	13.8	414W

3.2.3 Total ground station power budget

From the described analysis, the power budget can further be derived as shown in Table 3, assuming maximum power consumption during any time of the elements operation.

Table 3: The resultant power budget

Equipment	*Power rating*	*Time estimate*	*kWh*
Communication equipment	414W	1 hour/day	414Wh
Rotator/Azimuth	102/5min	5 mins (steps)	102Wh
PC(Computer)	60W	1 hour/day	60 W
		Total	**576Wh**

3.3 Ground station power consumption topology

From the analysis of Table 1, Table 2 and the PC power consumption, the interconnection of the Ground Station equipments and the resultant power topology can be represented by Figure 3.

3.4 The power consumption structure

Again using Tables1 and 2 and the PC power consumption, the power topology is further broken as illustrated in Tables 4 and 5 to allow flexibility in data analysis.

Table 4: Breakdown of ground station power use

PC computer	*Azimuth / controller*	*Communication equipments*	*Total power*
60W	0	0	60W
60W	49.7W	69W	178.7W
60W	50.7W	138W	248.7W
60W	88.1W	207W	350.1W
60W	99.3W	276W	435.3W
60W	101W	345W	506W
60W	102W	414W	576W

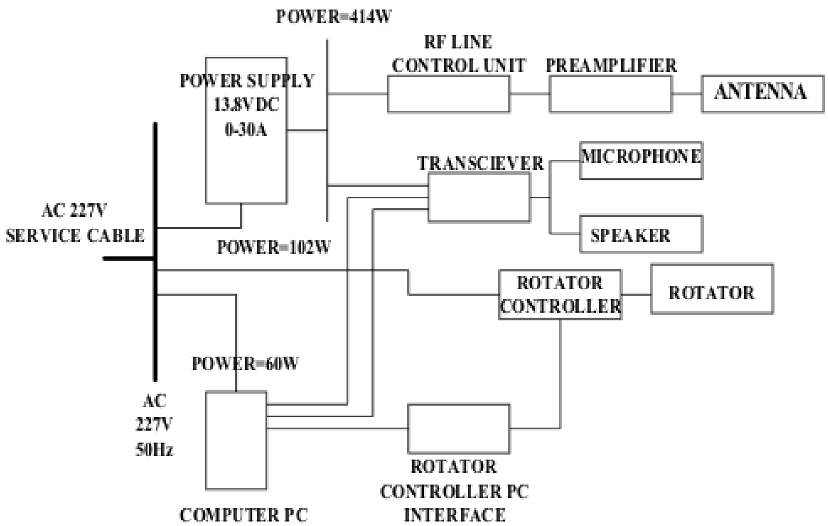

Figure 3: The resultant power topology

Table 5: Power consumption according to operation

Power rating	Ground station operation function
60W-178.7W	PC computer and communication equipment
178.8W-248.8W	Computer, communication and rotation functions
248.8W-300W	All functions (tracking and downloading of data)
300W-576W	All functions(tracking and downloading of data

3.5 The equivalent PV system topology

From Figure 3, the equivalent PV topology is designed as in Figure 4.The ratings and numbers of the components are determined focusing on the Ground Station power budget. The following formulas are used:

$$\text{Module daily output } (d/o) = \frac{I_M \times I_R \times 12V}{F_1 \times F_2} \quad (1)$$

Where

I_M = Module maximum power point current

I_R = Daily irradiation current

F_1 = Temperature correction factor

F_2 = Tilt angle correction factor

$$\text{Number of modules} = \frac{P_b(Wh/day) \times 100}{d/o \times b_t(\%)} \quad (2)$$

Where

$P_b(Wh/day)$ = Power budget

d/o = Module daily output

b_t = Battery charging efficiency (%)

$$\text{Battery usable capacity/day} = \frac{p_b(Wh/day) \times P_{st}}{V_m} \quad (3)$$

Where

$P_b(Wh/day)$ = Power budget

V_M = Total solar array output

$$\text{Number of batteries} = \frac{U_C(Ah) \times 100}{N_C \times D_{ch}} \quad (4)$$

Where

U_C = Battery daily usable capacity

N_C = Battery nominal capacity

D_{Ch} = Depth of discharge allowed

All other elements are also sized with reference to the ground station power budget. Table 6 is a list of components and their specification ideal for this project.

Table 6: List of the components and specification

Component	*Technical specification*	*Units*
Step-down Buck converter	20-28Vdc, 13.65-13.8Vdc, 40A	1unit
Sun module 50w, mono/R5A,	Voc 21.0v, Isc 3.40A Vmpp 16.2, Immp 3.10A	4units
Steca Solarix (Gamma) 12A	12/24, 12A Regulator with LED	1unit
Excis 12v 102Ah maintenance free battery	Cagrids and plates, glass backed separators	2units
Cotek 300w 24v pure sine wave inverter	S300-224220/230/240, start on demand	1unit
Earth leakage circuit breaker	25A 30Ma 2P DID overload	1unit
Cylindrical fuses	20mA-500v 100KA 10X38mm	2units
Circuit breakers	10Amp-AC	1unit
Econo fuse holder for cylindrical fuses	2P 32A-500V fuse holder 10X38mm	1unit
Blocking diode at life battery terminals	12Amps or 6 Amps rating	2 units
Wire PVC 1.5mmsq round white p/m	3 core cabtyre	8M
Plug/3pin /British standard	Plug top 13A	4 units
Socket outlets	13 Amp 3 Pin plug	6 units

4. Investigation and measurements

To determine the capability of the PV system logging in is done for a load representing a specific function of the Ground station. The time for logging is 1 hour, which represents time for two satellites downloads. The basis for logger measurements takes into account the following power based formulas:

$$V_{RMS} = \sqrt{\frac{1}{T}\int v^2 dt} \quad (5)$$

$$I_{RMS} = \sqrt{\frac{1}{T}\int i^2 dt} \quad (6)$$

$$THD = \frac{\sqrt{\sum_{n=2}^{40}(V_h)^2}}{V1} \times 100 \quad (7)$$

THD=Total harmonic distortion

The solar cell is the main converter of photon energy to electric energy. The cells are connected to

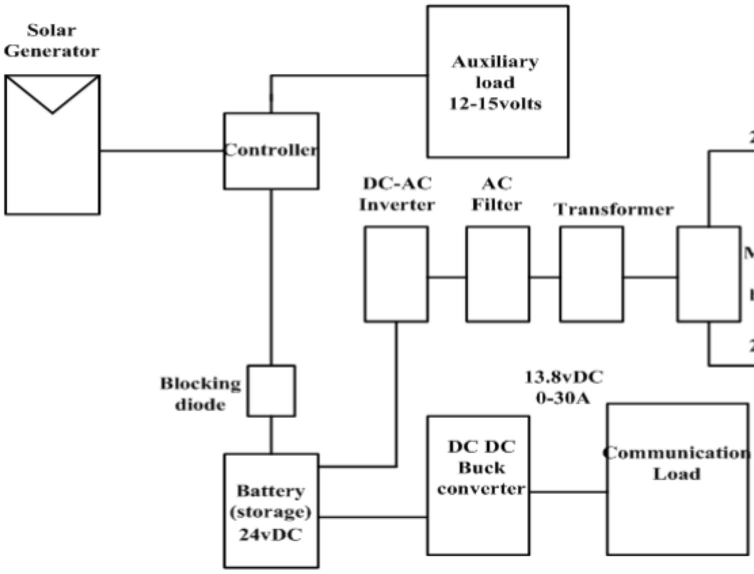

Figure 4: The designed PV topology

form solar panels. The panels are connected in parallel and placed at an angle of 45^0. Their production is about 200Wp.

The PV energy control centre consists of circuit breakers for circuit protection, charge controllers, inverters, step down DC/DC converters and the batteries. The incandescent bulbs are found the most ideal to analyse power consumption of the Satellite load, since they don't have a reactive component resulting to a pure sinusoidal output. Figure 5 illustrates this analysis connection.

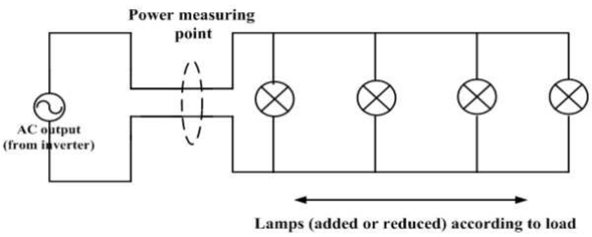

Figure 5: The mode of loading power drop

5. Logging and data taking

Measurement and logging is done to determine the capability of the PV system to power the Ground Station. The battery and the PV voltage are noted at the start and the end of the logging in period. The following is an illustration of successful logging in and the ultimate RMS value of voltage and current. This was repeated in consecutive days to come up with a good sample.

5.1 Data taken on 27/05/2012

On this date, the measurements for RMS values of current and voltage at 60W and 160W loads were determined. This was followed by logging in for one hour to analyse the variation of voltage and current with time. Table 7 indicates a summary of the measurements done on this date.

5.2 Data of 28/05/2012

On this date, it was possible to log in a 260W load, followed by a 300W load for a total of one hour. Table 8 indicates measurements of RMS of voltage, current and frequency at the start of the analysis followed by variation of these parameters during logging in period

Table 7: Summary for the loads analysed

LOAD 60W	V_{rms}	V_{min}	V_{max}	I_{rms}	I_{min}	I_{max}	F_e	*Min*	*Max*
V/A/Hz	122.3	0.1	125.7	5.07	4.91	5.42	50	0	50.1
VrmsxIrm	Prms	Pmin	Pmax						
Power (W)	620	0.491	681.3						
Logging	122.4	121.1	122.7	5.22	4.97	5.36			
Power (W)	638.9	594.6	657.7						
LOAD160W	120.6	120.1	122.1	5.13	4.80	5.38	50	49.9	50
Power (W)	653.9	624.2	673						
Logging	125.5	124.5	125.6	5.21	4.99	5.45			
Power (W)	653.9	621.3	684.5						

Table 8: Summary for the loads analysed

LOAD 260W	V_{rms}	V_{min}	V_{max}	I_{rms}	I_{min}	I_{max}	F_{req}	*Min*	*Max*
V/A/Hz	122.5	0.1	122.8	5.19	4.99	5.45	49.9	0	50.04
$V_{rms}xI_{rms}$	P_{rms}	P_{min}	P_{max}						
Power	635.8	0.499	669.3						
Logging	122.1	121.1	122.3	5.21	4.96	5.33			
Power	636.1	624.6	657.7						
LOAD									
300W	125.1	125.1	125.1	5.24	499	5.38	49.9	49.9	50
Power	653.9	624.2	673						
Logging	125.5	124.5	125.6	5.21	4.99	5.34			
Power	653.9	621.3	670.7						

5.3 Data of 29/05/2012

A 300W load was successfully logged this date. Table 9 indicates the RMS of voltage, current and frequency. This is followed by variation of these parameters with time during one hour logging in and the resultant PV system power.

Table 9: Summary for the loads analysed

Load 300W	V_{rms}	V_{min}	V_{max}	I_{rms}	I_{min}
V/A/Hz	119.5	0.1	120.5	5.11	4.91
Power (W)	610.6	0.491	650.7		
Logging (36min)	115.7	115.7	116.4	5.33	4.95
Power (W)	616.7	577.7	625.1		

5.4 Data of 30/05/2012: NO LOAD condition

On this date, the PV power system portrayed output characteristics as indicated in Table 10, which includes RMS voltage of 0.1V and a resultant average output RMS power of 0.555W. This implies that the PV power system is unable to power the ground station.

Table 11: Dates with NO LOAD conditions

Date	*Load*	*PV Power*	*Condition*
30/04/2012	160W	0.535W	No Load
02/05/2012	100W	O.495W	No Load
O6/05/2012	100W	0.495W	No Load
03/05/2012	100W	0.495W	No Load

6. Time plot for 360w load (05/05/2012)

The time plots are done to reveal the quality of the voltage and current supplied by the PV system during access time of the satellite. Figure 6 shows the voltage and current variations plotted against time for a load of 360W for the duration of 36 minutes. This load represents all the functions of the ground station. The study is to establish the capability to power the ground station and the quality of the voltage and current during its operation. Table 12 is the summary, while Table 13 represents the equivalent power variation during the logging in time.

6.1 Time plot for 400W loads (07/05/2012)

Figure 7 shows the voltage and current plotted against time for a load of 400W for duration of 36 minutes. The voltage drops with time while current

Table10: PV system NO LOAD characteristics

LOAD 160W	V_{rms}	V_{min}	V_{max}	I_{rms}	I_{min}	I_{max}	F_{req}	min	max
V/A/Hz	112.0	112.0	122.1	5.12	4.96	5.32	50	50	50
$V_{rms}xI_{rms}$	P_{rms}	P_{min}	P_{max}						
Power (W)	573.4	555.5	625.1						
Logging	0.1	0.1	0.1	5.33	4.95	5.37			
Power (W)	0.555	O.495	0.535						

Table 12: Summary current and voltage variation

Voltage variation		*Current variation*		
Time	*Normal period(RMS)*	*Time*	*Max(A)*	*Min(A)*
2:21.12PM	122.087V	2:21.56PM	5.4164A	5.1586 A
2:30.15PM	108.3043V	2:37.25 PM	5.3461 A	5.1 A
2:44.05PM	108.609V	2:44.46 PM	5.2484 A	5.1195 A
2:56.32PM	107.083V	2:56.27 PM	5.2641 A	5.1117 A

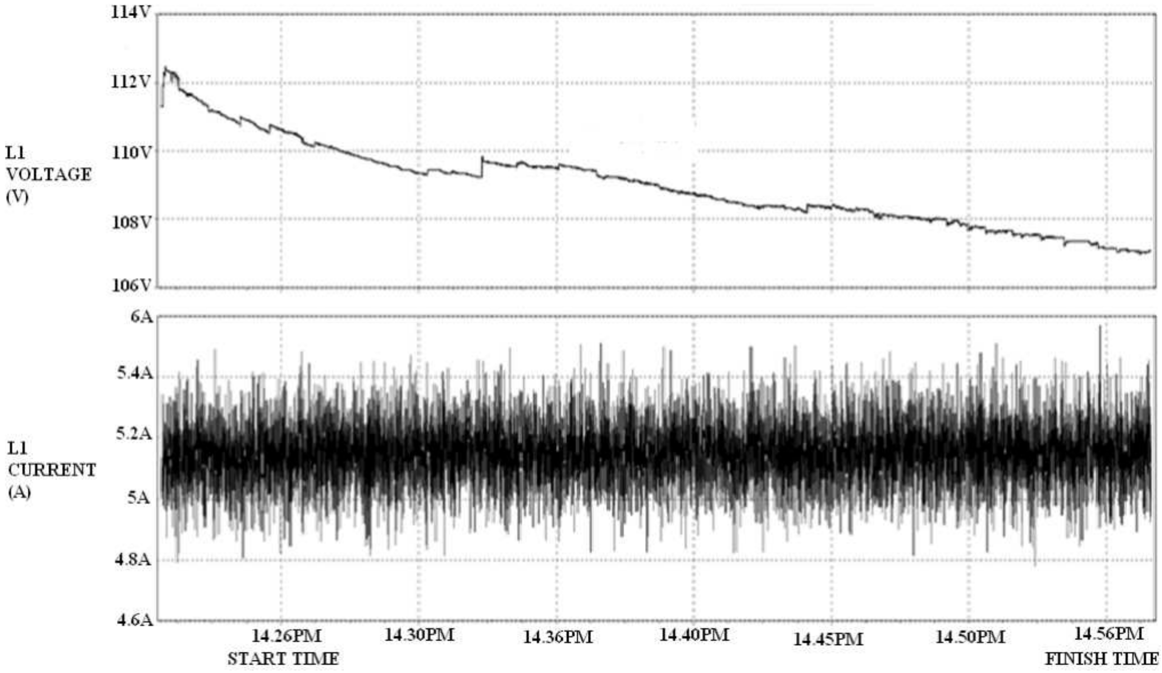

Figure 6: Voltage and current time plot for 360 W load

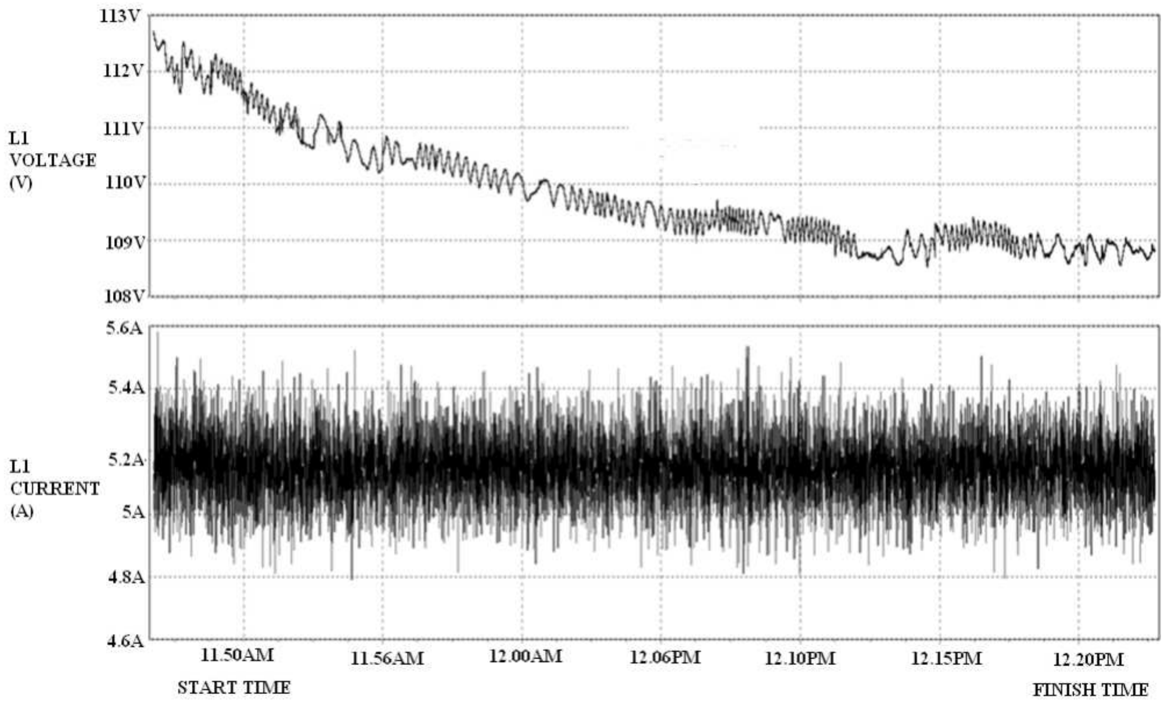

Figure 7: Voltage and current time plot for 400 W load

remains a constant plot. Table 14 is the summary of the variation with time and Table 15 is the equivalent variation of power with time for duration this time when tracking and downloading of data is in progress.

6.2 Summary of the measurements done

The parameters of the PV system monitored against the Ground station equivalent load are illustrated in Table 16.

7. Solar insolation considerations

Solar irradiance is the amount of sunshine received at any time during the day, while solar insolation is the amount of irradiance measured in the day. Solar irradiance varies throughout the day due to movement of the sun and cloud cover. In order to reach a conclusion on the reliability of the designed PV system, solar insulation and cloud cover must be taken into account.

Table 13: Equivalent power variation

	Load = 360W $P = V_{RMS} X I_{RMS}$	
Time duration	*Power (max)*	*Power (min)*
2:21.12PM	661.2W	629.8W
2:30.15PM	579W	552.4W
2:44.05PM	570W	556W
2:56.32PM	563.7W	547.4W

Table 14: Summary current and voltage variation

	Load = 400W $P = V_{RMS} X I_{RMS}$	
Time duration	*Power (max)*	*Power (min)*
11:47.04AM	662.8W	631.2W
11:59.22AM	577.4W	564W
12:13.07PM	573.1W	554W
12:22.07PM	563.6W	556.4W

7.1 Solar insolation and cloud cover

Solar insolation which is the average solar irradiation received in a day is measured in W/m^2. On a very clear day, the irradiance reaching the earth surface, facing the sun is $1000W/m^2$ (A.M1.5). From the data of Table 17, this is rearranged as in Table 18, which indicates percentage suns presence and the solar insolation level of the days the data was collected. From this table, solar insolation was only possible with a cloud cover of over 50%.

Table 17: Percentage cloud cover and solar insolation

Date	*Temperature range (C)*	*% sun presence (without clouds)*	*Solar insolation*
27/04/2012	$11^0 - 18^0$	30%	$40W/m^2$
28/04/2012	$12^0 - 19^0$	56%	$60W/m^2$
29/04/2012	$13^0 - 18^0$	63%	$80W/m^2$
30/04/2012	$14^0 - 19^0$	20%	$22.7W/m^2$
2/05/2012	$13^0 - 19^0$	40%	$12W/m^2$
3/05/2012	$12^0 - 18^0$	40%	$12.2W/m^2$
4/05/2012	$12^0 - 18^0$	35%	$45.6W/m^2$
5/05/2012	$12^0 - 21^0$	65%	$75.6W/m^2$
6/05/2012	$13^0 - 20^0$	50%	$12.2W/m^2$
7/05/2012	$13^0 - 20^0$	65%	$89.6W/m^2$

8. Results and analysis

8.1 Insolation PV voltage and battery

For insolation level of over $50W/m^2$, the PV voltage ranged between 14.83V to 13.1V on no load and 14.3 to 12.2V on load, while the battery voltage varied between 13.95 and 12.1 on no load and 13.06 to 11.8 on load. This shows solar insolation level and the cloud cover had a direct impact on PV and battery output.

8.2 Insolation, PV voltage and the load

From Table 19, it can be deduced that, for the insolation level of over $40W/m^2$, the PV AC voltage var-

Table 15: Equivalent power variation

Voltage variation			*Current variation*	
Time	*Normal period (RMS)*	*Time*	*Max (A)*	*Min (A)*
11:47.04AM	122.5435V	11:47.33AM	5.4086A	5.1508 A
11:59.22 AM	110.2609V	11:58.26 AM	5.2367 A	5.1156 A
12:13.07PM	108.8696V	12:12.18 PM	5.2641 A	5.0688 A
12:22.14PM	108.8478V	12:22.32 PM	5.1781 A	5.1117 A

Table 16: PV parameters and load analysed

Date	*PV voltage*		*Battery voltage (V)*		*Charging current(A)*		*AC output*	*Max load (W)*
	Start	*Finish*	*Start*	*Finish*	*Start*	*Finish*	*V*	
27/04/12	12.9V	12.V	12.3	11.9V	1.49A	-0.03	226.7	160W
28/04/12	13.6V	12.6V	12.1	11.8V	4.36A	1.6	230V	300W
29/04/12	13.1V	11.9V	12.1	11.1V	1.24A	0.5	226.7	300W
30/04/12	12.3V	11.8V	11.	11.1V	0.65A	-0.03	220.	160W
2/05/12	12.47V	10.47V	12.2	10.74V	0.52A	-0.03	225.3	100W
3/05/12	11.83V	11.6V	11.71	11.2V	0.48A	-0.01	224.6	100W
4/05/12	12.4V	12.20V	12.1	12.0V	0.34A	0.01	228.6	260W
5/05/12	14.31V	13.54V	13.02	12.44V	5.10A	4.30	229.8	360W
6/05/12	12.3V	10.06V	11.8	11.3V	0.32A	-0.01	223	100W
7/05/12	14.88V	14.33V	13.95	13.6V	4.41A	2.0	229.	400W

Table 18: Solar insulation, PV system and battery

Date	*% sun presence (without clouds)*	*Solar insolation*	*PV voltage*		*Battery voltage*	
			Start	*Finish*	*Start*	*Finish*
27/04/12	30%	40W/m^2	12.9V	12.V	12.3V	11.9V
28/04/12	56%	60W/m^2	13.6V	12.6V	12.1V	11.8V
29/04/12	63%	80W/m^2	13.1V	11.9V	12.1V	11.1V
30/04/12	20%	22.7W/m^2	12.3V	11.8V	11.6V	11.1V
2/05/12	40%	12W/m^2	12.47V	10.47V	12.26V	10.74V
3/05/12	40%	12.2W/m^2	11.83V	11.6V	11.71V	11.2V
4/05/12	35%	45.6W/m^2	12.4V	12.20V	12.12V	12.0V
5/05/12	65%	75.6W/m^2	14.31V	13.54V	13.02V	12.44V
6/05/12	50%	12.2W/m^2	12.3V	10.06VV	11.8V	11.3V
7/05/12	65%	89.6W/m^2	14.88V	14.33V	13.95V	13.06V

Table 19: Solar insolation, PV voltage and load

Date	*% sun presence (without clouds)*	*Solar insolation*	*AC output*	*Max load (W)*
27/04/12	30%	40W/m^2	226.7V	160W
28/04/12	56%	60W/m^2	230V	300W
29/04/12	63%	80W/m^2	226.7V	300W
30/04/12	20%	22.7W/m^2	220.V	160W
2/05/12	40%	12W/m^2	225.3V	100W
3/05/12	40%	12.2W/m^2	224.6V	100W
4/05/12	35%	45.6W/m^2	228.6V	260W
5/05/12	65%	75.6W/m^2	229.8V	360W
6/05/12	50%	12.2W/m^2	223V	100W
7/05/12	65%	89.6W/m^2	229.8V	400W

Table 20: Solar insulation, power, and ground station

Date	*% sun presence (without clouds)*	*Solar insolation*	*Max load (W)*	*PV power (max)*	*Ground station function*
27/04/12	30%	40W/m^2	160W	674.5W	PC+ communication
28/04/12	56%	60W/m^2	300W	670.7W	Azmuth+ rotator + communication
29/04/12	63%	80W/m^2	300W	625.1W	Azmuth+ rotator + communication
30/04/12	20%	22.7W/m^2	160W	0.545W	PC (no load)
2/05/12	40%	12W/m^2	100W	0.495W	PC (no load)
3/05/12	40%	12.2W/m^2	100W	0.495W	PC (no load)
4/05/12	35%	45.6W/m^2	260W	669.3W	Azmuth+ rotator + communication
5/05/12	65%	75.6W/m^2	360W	661.2W	Azmuth + rotator + communication
6/05/12	50%	12.2W/m^2	100W	0.495W	PC (no load)
7/05/12	65%	89.6W/m^2	400W	662.8W	Azmuth+ rotator + communication

ied between 226.7VAC and 229.8VAC. Full Ground Station operation (over 260W) was only possible with over 45W/m^2 insolation level. Thus solar insolation level had a direct impact on AC voltage and Ground Station Load.

8.3 Insolation, power and ground station function

Table 20 illustrates the relationship between solar irradiation, maximum load, PV system maximum power and the ground station function. The

Maximum PV power varied from 684.5W to 661.2W. For all the functions of the Ground Station to be attained solar insulation should be at least $45W/m^2$. The success of the system depends on proper design of its components, the cloud cover and solar insolation level.

9. Conclusions and recommendations

A hallmark of this research is that with solar irradiation as low as $50W/m^2$ the designed PV system can successfully power the ground station for one hour continuously, which involves satellite tracking and downloading of data. The PV panels were designed to operate at an irradiance of $800W/m^2$. The power budget of the satellite ground station is at a maximum at 567W, while the PV designed system is capable of a maximum power ranging from 684.5W and 554W. From the logged data, the current remains almost constant with time, while voltage falls. It's found that if the battery is at a low of 10.9V, this is a NO LOAD condition.

- The system is expected to operate with over 90% efficiency and reliability in the Free State, North West, Limpopo, interior parts of the Western and Eastern Cape and parts of Africa where solar insolation levels are over $100W/m^2$.
- For locations with lower insolation levels, larger solar PV panels are recommended.
- This methodology is recommended for any load, to reduce power wastage, cost and improve on system reliability and the availability of load in PV standalone systems.

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Received 7 October 2012; revised 24 May 2014

Optimization and effects of process variables on the production and properties of methyl ester biodiesel

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Abstract
Optimization of the production process in biodiesel production holds huge prospects. A reduced cost option is the optimization of process variables that affect yields and purity of biodiesel, which was achieved in this study. Optimized production and direct effects of process variables on the production and quality of methyl ester biodiesel fuels from the non-edible seed oils of sandbox seed was carried out. Catalyst nature and concentration, alcohol to triglyceride molar ratio, mixing speed, reaction time and temperature were taken into consideration as variables to their individual response on the yields, viscosity and specific gravity of the methyl esters produced. These are specific indispensable properties of biodiesel for use in compression ignition engines. Optimized concentrations were 0.3 to 1.5% w/v and two mole ratios of 3:1 and 6:1. Time of reaction was varied (5mins to 30mins) with temperatures (38oC and 55oC). Also, the effect of methanol in the range of 4:1and 6:1 (molar ratio) was investigated, keeping catalyst type, reaction time and temperatures constant. The effects of KOH and NaOH on the transesterification were investigated with concentration kept constant at 1%. The general response in this study was that at optimized rate of agitation (800rpm), optimized reaction time was as low as 5minutes, 1% catalyst concentration of NaOH was the optimal concentration, and 55oC was the optimal temperature with attendant high yields. However, there are variations with the nature of feedstock as the work further exposed. These high points are particularly of interest to guide against process backdrop.

Keywords: optimization, process variables, effects, methyl esters, production, sandbox seed oil

1. Introduction

Biodiesel possessing the best properties were obtained using potassium hydroxide as catalyst in many studies (Encinar *et al.,* 2005, Jeong and Park, 1996, Darnoko and Cheryman, 2000, Ugheoke *et al*., 2007, El Mashad *et al.*, 2006). Besides, many other studies achieved best results using NaOH (Felizardo *et al*., 2006, Vicente *et al*., 2004, Cheng *et al*., 2004, de Oliveira *et al*., 2005). Methanolysis with 1%wt of either sodium hydroxide or potassium hydroxide catalyst resulted in successful conversion giving the best yields and viscosities of the esters in most of the literature reviewed. It was observed that the product volume steadily increased from 0.5% w/v concentration of the catalyst until it reaches its peak at 0.9% wt/ v catalyst concentration. Thereafter, a decrease was witnessed. Catalyst concentration levels greater than 1% may have favoured the reverse reaction (El Mashad *et al*., 2006).

One of the most important variables affecting the yield of ester is the molar ratio of alcohol to triglyceride. The stoichiometric ratio for transesterification requires three moles of fatty acid alkyl esters and one mole of glycerol. However, transesterification is an equilibrium reaction in which a large excess of alcohol is required to drive the forward reaction. For maximum conversion to the ester, a molar ratio of 6:1 was mostly used (Cheng *et al.*, 2004, Jeong and Park, 1996, Darnoko and Cheryman, 2000, Meka *et al.*, 2007, Ugheoke *et al*., 2007, Encinar *et al*., 2005).

In other studies, the optimum ratio was 10:1 (Jeong and Park, 1996, Cheng *et al.*, 2004, Karmee and Chadha, 2005). In this study, optimization of the production process was conducted and the effects of process variables obtained as they affect the yields, purity and important properties of the methyl ester which will be obtained during the trans-esterification process with the aim of reducing cost and achieving high level purity biodiesel that will be comparable with ASTM standards. This assisted in producing different grades of methyl esters and blends while the ones at optimal conditions were also established with reduced costs, better properties, effects, high yields and purities attained. The effects of transesterification variables on the yields and properties of biodiesel of four tropical seed oils were earlier studied by Igbum *et al*. (2012), which gave a leeway to the present study as sandbox seed oil was also evaluated. The objective of the present study therefore was to optimise the application of the process variables and ascertain the effects thereof on the production process and properties of the methyl ester biodiesel thereby reducing the cost and rigours of production.

2. Materials and method

2.1 Seed plant of study: Hura crepitans L

The Sandbox tree (*Hura crepitans*; syn. *Hura brasiliensis* Wild.), also known as Possum wood and Jabillo, is an evergreen tree of the spurge family (*Euphorbiaceae*), native to tropical regions of North and South America in the Amazon rain forest. Oils extracted from the derived seeds are also used as a purgative. Its pale, yellow or brown soft wood is used for furniture under the name Hura. In summary, the sandbox tree often can be found in nearly pure stand on most loam soil in the flat coastal regions. The leaves are used against eczema. In Africa, it's invasiveness in Tanzania was reported (Rejmanek, 1996). The seeds were collected from the Makurdi metropolis, Nigeria, during the dry season (December-February). The seeds usually fall to the ground during the dry season; for this study, they were sun dried for several weeks and then crushed whole, milled and grounded together with the hard cotyledonous shells. This was due to the toughness of the shell, which could not be easily separated from the mesocarp. The ground seeds were sieved to remove shells before extraction.

2.2 Preparation of methyl esters

100ml of *Hura crepitans* oil was measured, and poured into a large beaker. The oil was pre-treated by heating to a temperature of 70°C using a Bunsen burner to remove the remains of solvent or moisture content and the temperature was monitored using a thermometer until it dropped to the required temperature. The heated oil was then poured into a blender, and switched off the prepared methoxide from the PET bottle, which was emptied into the oil in the blender and the blender switched on, the mixture was blended for the required time of mixing.

The blender was switched off and allowed to stop rotating. The mixture was immediately transferred from the blender to a one litre PET bottle and closed tightly. The PET bottle occasionally opened to allow some air into the PET bottle in order to avoid contraction due to cooling of the oil. The mixture was allowed to settle for 24 hours after which a dark colour glycerine by-product was observed separated from the pale liquid above with the biodiesel at the top layer. It should be noted that the biodiesel varies somewhat in colour according to the oil used and so does the by-product layer at the bottom (Van Gerpen *et al.*, 2002 -2004). Optimization procedures were based on a repetitive process controlled by calibrated factors, depended and independent. This included: alcohol/oil mole ratio (6:1 and 4:1), temperature of reaction (38, 55°C), reaction time (5, 30s), reaction speed, catalyst type and concentrations (KOH and NaOH); while the properties considered are: biodiesel/methyl ester yields, specific gravity, viscosity, fatty acid composition and others that are not reported in this report.

2.3 Biodiesel separation

Once the reaction was completed, two major products existed: glycerine and biodiesel. The clear liquid (biodiesel) found at the top layer was decanted into a graduated beaker, the remains which was difficult to decant was then transferred into a separatory funnel and allowed to settle (Figure 1 c). The stopcock of the separatory funnel was opened and glycerine was first collected because it forms the lower layer of the mixture. The remaining liquid which was difficult to decant was transferred into a separatory funnel and allowed to settle. The stopcock of the separatory funnel was opened and glyc-

Figure 1: a. Fully grown pods of *Hura crepitans* seed hanging on the tree; b. pulverized Hura seeds; and c. Biodiesel and glycerine after separatio

erine collected first because it forms the layer below. The remaining top layer which is the biodiesel was siphoned off into a beaker. In some cases, a centrifuge is used to separate the two materials (Rejmanek, 1996).

2.4 Biodiesel washing

The biodiesel was turned into a separatory funnel and covered by a lid; an equal amount of tap water was added. The funnel swirled severally, after which it was allowed to settle for some few minutes and the water drained off from the bottom by opening the stopcock. This procedure was repeated twice using two different separatory funnels. In each washing, a separatory funnel is used until washing was affected. After washing, the biodiesel was heated to 100^0C and allowed to cool. The essence of the heating was to dry the oil (Rejmanek, 1996).

2.5 Determination of the effects of Catalyst type on yields and specific properties

Base catalysts (NaOH and KOH) were used. Catalyzed processes dominate current commercial production. These reactions are relatively fast but are sensitive to water content and free fatty acids. Typical base concentrations are 0.3 to 1.5% based on the weight of oil. When sodium methoxide is used, the concentration can be 0.5% or less. Most researchers use NaOH as the catalyst. There are some operations that use KOH, in spite of the higher cost, because the potassium can be precipitated as K_3PO_4 fertilizer when the products are neutralized using phosphoric acid. However, this can make meeting water effluent standards a bit more difficult because of limits on phosphate levels.

2.6 Preparation of methoxide

To prepare methoxide, 1g of KOH or NaOH was measured into a handy-sized light plastic bag using the scale (weighing balance). 20ml of methanol was also measured using a graduated measuring cylinder and this was turned into a PET bottle. The KOH or NaOH from the plastic bag was mixed with the methanol and the container closed tightly, the container was swirled several times until all the lye was completely dissolved (Rejmanek, 1996).

2.7 Determination of the effects of alcohol/oil molar ratio on yields and specific properties

Usually 60% to 100% excess methanol is added to ensure that the reaction goes to completion. In general, the reaction can be encouraged to progress by adding an excess of one of the reactants or by removing one of the products. A base catalysed process typically uses an operating mole ratio of 6:1 of alcohol rather than 3:1 ratio required by the reaction. The reason for using extra alcohol is that it drives the reaction closer to the 99.7% needed to meet the total glycerol standard for fuel grade biodiesel, the unused alcohol must be recovered and recycled back into the process to minimize operating cost and environmental impacts. Methanol is considerably easier to recover than ethanol. Therefore, two mole ratios of 4:1 and 6:1 were used.

2.8 Determination of the effects of reaction time on yields and specific properties

Based catalysed reactions are relatively fast, with residence times from about 5 minutes to about 1 hour, depending on temperature, concentration, mixing and alcohol: triglyceride ratio (Burkil, 1994). The typical procedure is as already described. Time of reaction was varied at 5mins to 30mins due to the speed of the mixer. It is important to note that, there is a conversion of the triglycerides to di-glycerides and then mono-glycerides/glycerol. If the reaction does not go into completion, mono-glyceride/glycerol separation will not take place and therefore the methyl ester will not meet ASTM standards. An ASTM standard for total and free glyceride specifies the minimum amount retainable in any completely reacted transesterified methyl ester. The requirements are 0.25% maximum and 0.02% maximum for total and free glyceride respectively. These parameters are very important in biodiesel development to determine complete or incomplete transesterification reaction and the quality of the products.

2.9 Determination of the effects of temperature on yields and specific properties

Temperature had no detectable effect on the ultimate conversion to ester. However, highest temperatures decrease the time required to reach maximum conversion (Burkil, 1994). Since this reaction is between the liquids and also due to the fact that fats and alcohols are not totally miscible, transesterification therefore will be a relatively slow process. As a result, a vigorous mixing is required to increase the area of contact between the two immiscible phases (Ma *et al.*, 1999). Temperature will be varied between 38°C and 55°C, which is below the boiling point of methanol.

3. Results and discussion

3.1 Effects of alcohol/oil molar ratio on the yields and specific properties of Hura vegetable oil methyl esters (HVO-ME)

One of the most important parameters affecting the yield of ester is the molar ratio of alcohol to vegetable oil. The stoichiometry of the transesterification reaction requires 3:1 molar ratio to yield 3 mol of ester and 1 mol of glycerol, but most researchers found that excess alcohol was required to drive the reaction close to completion. In this work, methanol was used. The effect of methanol in the range of 4:1and 6:1 (molar ratio) was investigated, keeping catalyst type constant; catalyst type, reaction time and temperature were varied with each reaction keeping one or two variable(s) constant at a time. It was found that the ester yields increase with molar ratio of 6:1 with 97% yield for HVO-ME (Figure 2, Table 1, Figure 4). Lower yields were obtained when the molar ratio of 4:1 was used. For low values of molar ratio, the ester yield was sensitive to the concentrated NaOH for HVO-ME. The specific gravity of the ester does vary for the two molar ratios used; HVO-ME did not show specific trends in the values of specific gravity that can be believed to be as a result of the effects of molar ratio rather, the trends suggest that these results emanate from the catalyst type used. Figure 2 shows this evidence. Specific gravity was best with NaOH as well. HVO-ME showed viscosities that were within specification for 6:1 and 4:1 with only one catalyst type (NaOH) as shown in Figures 2 to 6. Therefore, once more, it can be observed that the alcohol/oil molar ratio has no effect on the viscosity of this methyl ester although viscosities were greatly enhanced with NaOH catalyst as shown rather than KOH.

3.2 Effect of reaction time

The mixing intensity appears to be of particular importance for the transesterification process. It increases the impact area between oils and catalyst-methanol solution. Mixing facilitates, the initiation of the reaction. Without mixing, the reaction occurred only at the interface of the two layers and are considered too slow to be feasible. In this study, a stirring rate of 800rpm was used. The yields, viscosity and specific gravity of methyl esters are shown in Figures 3, 5 and 6 and Tables 2 to 6. It was observed that the reaction of methanolysis was optimally completed at 5 minutes of mixing due to the speed of the rotor. For all cases, looking at the yields, viscosities and specific gravity, these did show significant difference when the time of mixing was increased (Ma *et al.,* 1999) and (Keith, 2010), the effect of agitation on the transesterification of vegetable oil was studied and concluded that higher agitation promoted the homogenization of the reactant and thus lead to higher yields. Also Rashid and Anwar (2008) in his research noted that the yield of methyl esters at 360rpm and 600rpm was the same, which is 96% after 2 hours of reaction.

This goes to show that if the rate of agitation is very high, the time of mixing can be reduced to as low as 5 minutes of reaction as can be deduced. This is because at 5 minutes, high yields (80%) were equally obtained for HVO-ME using KOH (Figure.5). Specific gravity and viscosities within specification were also obtained when a reaction time of 5 minutes was used especially with NaOH.

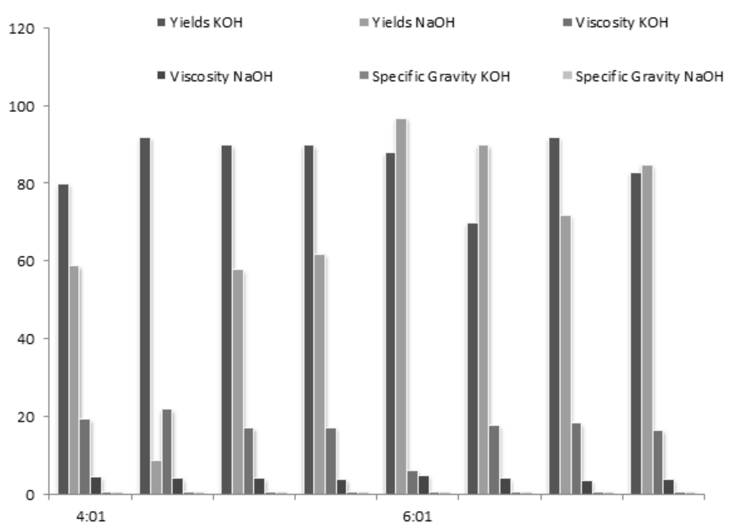

Figure 2: Effects of alcohol/oil ratio on some specific gravity and yields

Table 1: Alcohol/oil ratio on acid value, refractive index, carbon residue and sulphated ash

	AV (mgKOH/g)		*RI (limitless)*		*CR (% mass)*		*SA (% mass)*	
NaOH (replicates)	*4:1*	*6:1*	*4:1*	*6:1*	*4:1*	*6:1*	*4:1*	*6:1*
	0.561	0.560	1.466	1.467	0.016	0.019	0.004	0.010
	0.561	0.560	1.467	1.452	0.016	0.014	0.005	0.007
	0.561	0.560	1.467	1.452	0.017	0.017	0.006	0.006
	0.561	0.560	1.467	1.451	0.014	0.013	0.004	0.006

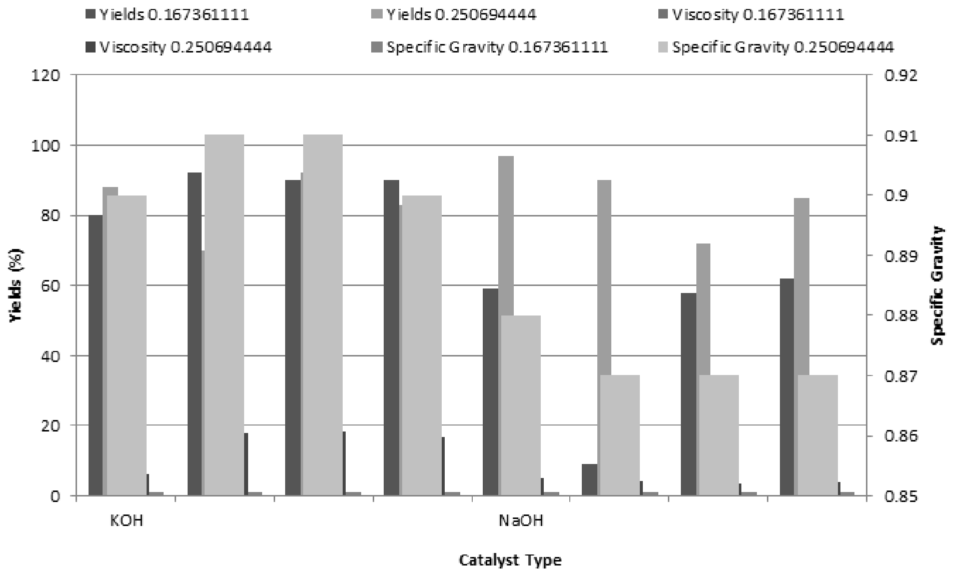

Figure 3: Effects of catalyst type on some specific chemo-physical properties

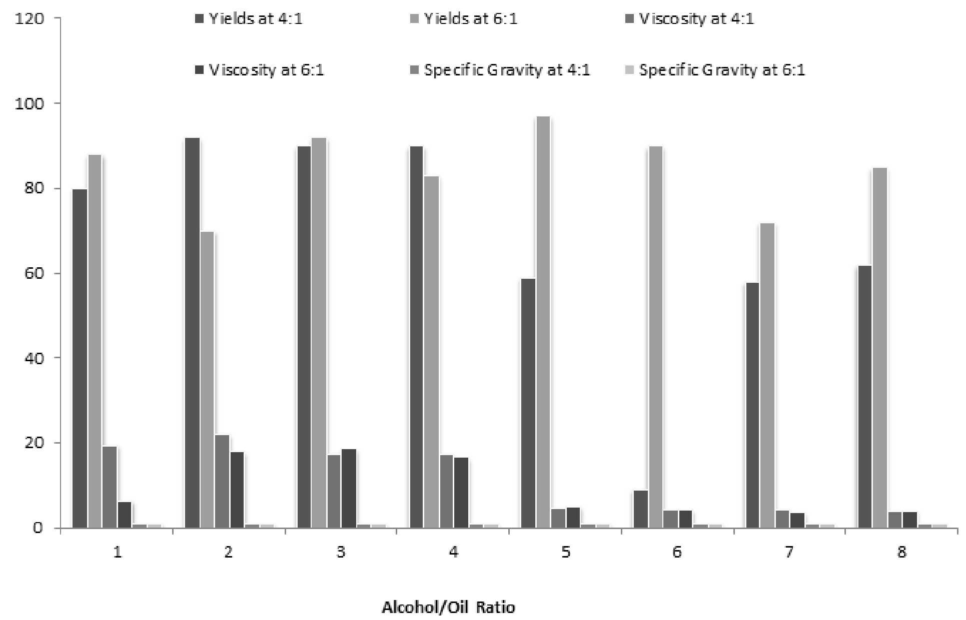

Figure 4: Effects of alcohol/oil ratio on some specific chemo-physical properties

Leung and Guo (2006), in their work, observed that ester content increases with reaction time at the beginning, reached a maximum at a reaction time of 15minutes at 70^{0}C, and then remained relatively constant with increasing further the reaction time. The results on an extension of the reaction time from 15minutes to 30 minutes had no significant effect on the conversion of triglycerides, but lead to a reduction in the product yield, the yield of the product with the same ester content decreased from 87.5% to 85.3%, dropped by about 2%. This is because longer reaction enhanced the hydrolysis of esters (reverse reaction of transesterification), resulting in a loss of esters as well as causing more fatty acid to form soap.

3.3 Effects of catalyst type on yields, viscosity and specific gravity of methyl esters

The effects of KOH and NaOH on the transesterification of the oils were investigated with the concentration kept constant at 1%. Figure 3 shows the effects. This effect on ester yields as can be observed from Figures 4 to 6, showed that both NaOH and KOH catalysts exhibited the appreciable behaviour especially at the ratio of 6:1, where NaOH also gave gave the best yield (97%) while it was poor at 4:1. Increase in reaction time from 5 minutes to 30 minutes did not improve the yields and viscosities for HVO-ME as earlier established. It also has no significant effects on specific gravity. Alcohol/oil molar ratio and the nature of catalyst

Table 2: Reaction time on water and sediment, flash point and cloud point

	W & S (% vol)		*FP (°C)*		*CP (°C)*	
NaOH	*5*	*30mins*	*5*	*30mins*	*5*	*30mins*
4:1	0.10	0.05	140	148	+1	+1
	0.10	0.10	142	146	-1	+1
6:1	0.05	<0.05	136	126	0	+4
	<0.05	<0.05	134	130	0	+4

Table 3: Reaction time on pour point, total and free glycerine of HVO-ME

	PP (°C)		*TG (% mass)*		*FG (% mass)*	
NaOH	*5*	*30 mins*	*5*	*30 mins*	*5*	*30 mins*
4:1	-4	-4	0.126	0.129	0.006	0.006
	-6	-4	0.141	0.129	0.006	0.005
6:1	-9	-6	0.108	0.124	0.005	0.006
	-9	-3	0.107	0.124	0.002	0.007

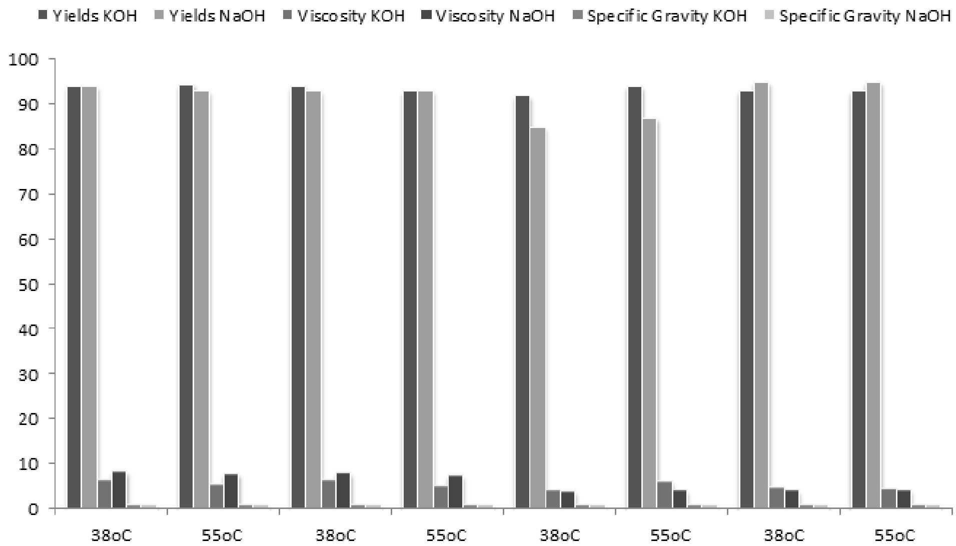

Figure 5: Effects of reaction temperature on some specific chemo-physical properties

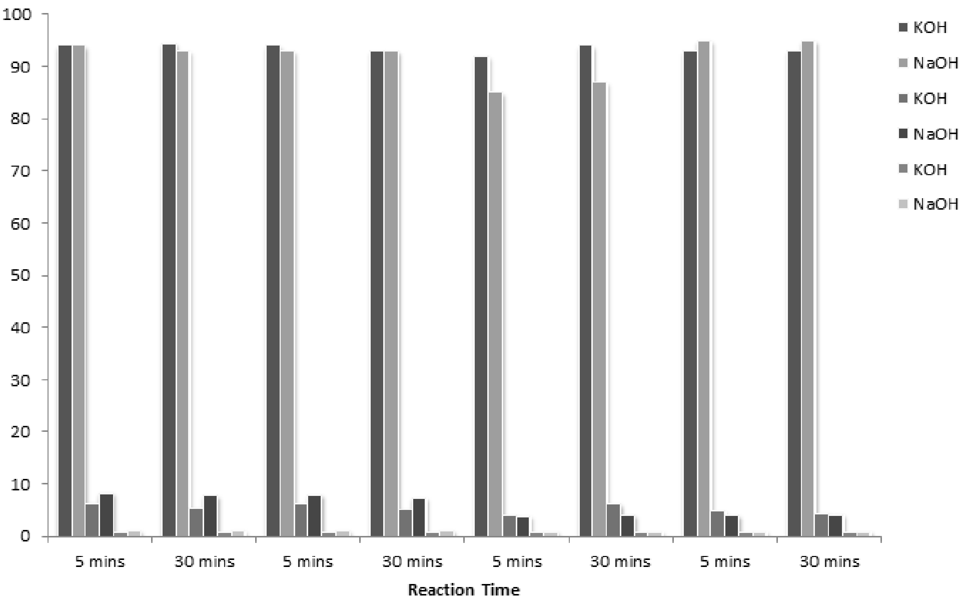

Figure 6: Effects of reaction time on some specific chemo-physical properties

can be thought to be responsible for the variation in yields, viscosity and specific gravity.

3.4 Effects of temperature on yields, viscosity and specific gravity

Alkaline alcoholysis of vegetable oils is normally performed near the boiling point of the alcohol (Neff *et al.,* 1992, Demirbaş, 1998). The reaction temperature above boiling point of alcohol is ignored because at high temperature, although it seems to accelerate the saponification of glycerides by the base catalyst before completion of the alcoholysis (McCormick *et al.*, 2007). In this study, experimental trials were carried out at temperatures of 38^0C and 55^0C. Figure 5, Tables 5 and 6 show the effect of temperature on yields, viscosities and specific gravity as analysed. Several researchers found that the temperature increase influences the reaction in a positive manner (Janarthan *et al.,* 1996, Knothe and Steidley, 2005, Pramanik, 2003, Dorado *et al.*, 2004, Srivastava and Prasad, 2000, ASTM, 2007). It was found that the ester yield slightly decreases above 50^0C reaction temperature. It may probably be due to a negative interaction between the temperature and catalyst concentration following the side reaction of saponification (Shailendra *et al.,* 2008, Ramadhas). High process temperature tends to accelerate the saponification of the triglycerides by the alkaline catalyst before completion of the transesterification process. Sinha *et al.* (2008) in their study concluded that the effect of reaction temperature on the ester yield and the viscosity of the ester decreases as the reaction temperature increases above 55^0C. An insignificant increase in the ester viscosity with reaction temperature is observed.

From the figures and tables shown, the increase in temperature did not improve the yield, viscosities and specific gravity of the methyl esters. This may be because as the reaction proceeds, there is increase in temperature naturally. Samples were introduced at 55^0C during reaction; an increase in temperature as reaction proceeds further was due to interaction during mixing above 55^0C which do not favour an increase in yields, viscosities and specific gravity.

Table 4: Effect of reaction time on acid value, refractive index, carbon residue and sulphated ash

	AV (mgKOH/g)		*RI (limitless)*		*CR (% mass)*		*SA (% mass)*	
NaOH	*5*	*30mins*	*5*	*30mins*	*5*	*30mins*	*5*	*30mins*
4:1	0.561	0.561	1.466	1.467	0.016	0.017	0.004	0.006
	0.561	0.561	1.461	1.467	0.016	0.014	0.005	0.004
6:1	0.560	0.560	1.467	1.452	0.019	0.017	0.010	0.006
	0.560	0.560	1.452	1.452	0.014	0.013	0.007	0.006

Table 5: Effect of reaction temperature on water and sediment, flash point and cloud point of HVO-ME

	W & S (% vol)		*FP (%)*		*CP (%)*	
NaOH	*38^0C*	*55^0C*	*38^0C*	*55^0C*	*38^0C*	*55^0C*
4:1	0.10	0.10	148	142	+1	-1
	0.05	0.10	148	146	-1	+1
6:1	0.05	<0.05	136	134	0	0
	<0.05	<0.05	126	130	+4	+4

Table 6: Effect of reaction temperature on pour point, total and free glycerine

	PP (°C)		*TG (% mass)*		*FG (% mass)*	
NaOH	*38^0C*	*55^0C*	*38^0C*	*55^0C*	*38^0C*	*55^0C*
4;1	-4	-6	0.129	0.129	0.006	0.009
	-4	-4	0.126	0.141	0.006	0.005
6:1	-9	-9	0.108	0.107	0.005	0.002
	-6	-3	0.124	0.124	0.006	0.007

W & S: water and sediments
FP: flash point
CP: Cloud Point
PP: Pour points
TG: Total glycerine
FG: Free glycerine
AV: Acid value
RI: Refractive Index
CR: Carbon residue
SA: Sulphated ash

4. Conclusion

In this study, 1% catalyst concentration which is the optimal concentration was used and established. An increase or decrease may affect the yield, viscosity and specific gravity of these methyl esters. Temperature had no detectable effect on the ultimate conversion to ester.

However, higher temperature decreases the time required to reach maximum conversion (Burkil, 1994). Since this reaction is between the liquids and also due to the fact that fats and alcohols are not totally miscible, transesterification is a relatively slow process. As a result, a vigorous mixing is required to increase the area of contact between the two immiscible phases.

Mixing is very important in the transesterification reaction, as oils or fats are immiscible with sodium hydroxide-methanol solution. Methanolysis was conducted at different reaction speeds of 180, 360 and 600 rpm (revolution per minute); the yield of methyl esters versus time at different rate of mixing was influenced. It was observed that the reaction was incomplete at 180rpm, while the rate of mixing at higher speeds favoured biodiesel yields and was significant for methanolysis. The yield of methyl esters at 360rpm and 600rpm was the same producing 97% after three hours of reaction time. These results are in accordance with standards already established in other studies (Ma *et al.,* 1999).

Acknowledgement

The authors hereby acknowledge the Centre for Engineering Postgraduate Studies (CEPS) of the University of KwaZulu-Natal for their funding/Doctoral CEPS bursary. Prof Nelson Ijumba and Prof. Innocent Davidson are specially mentioned.

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Received: 21 June 2013 revised 15 May 2014

Voltage stability enhancement using an adaptive hysteresis controlled variable speed wind turbine driven EESG with MPPT

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Abstract

This paper investigates the enhancement in voltage stability achieved while connecting a variable speed wind turbine (VSWT) driven electrically excited synchronous generator (EESG) into power systems. The wind energy conversion system (WECS) uses an AC-DC-AC converter system with an uncontrolled rectifier, maximum power point tracking (MPPT) controlled dc-dc boost converter and adaptive hysteresis controlled voltage source converter (VSC). The MPPT controller senses the rectified voltage (VDC) and traces the maximum power point to effectively maximize the output power. With MPPT and adaptive hysteresis band current control in VSC, the DC link voltage is maintained constant under variable wind speeds and transient grid currents.The effectiveness of the proposed WECS in enhancing voltage stability is analysed on a standard IEEE 5 bus system, which includes examining the voltage magnitude, voltage collapse and reactive power injected by the systems. Simulation results show that the proposed WECS has the potential to improve the long-term voltage stability of the grid by injecting reactive power. The performance of this scheme is compared with a fixed speed squirrel cage induction generator (SCIG), a variable speed doubly-fed induction generator (DFIG) and a variable speed permanent magnet synchronous generator (PMSG).

Keywords: variable speed wind turbine, EESG, MPPT, adaptive hysteresis band current control, SCIG, DFIG, PMSG, voltage stability

1. Introduction

Wind power generation has received considerable attention worldwide in recent years (Hansen *et al.*, 2007) and the effective utilization of wind energy has been an important issue. As a result, VSWT systems with power electronics interfaces have attracted much interest.

The VSWT systems are usually based on DFIGs or PMSGs (Akie Uehara *et al.*, Heng Nian *et al.*, Itsaso Martinez *et al.*, Alejandro Rol´an *et al.*, Si Zhe Chen *et al.*, Manuel Pinilla *et al.*, 2011). For the same power rating, the PMSG's cost is more than that of induction generator (IG) cost. But PMSG's have higher efficiency and so the higher material cost will be somewhat compensated by the extra electricity generated. Also IG's require capacitors for power factor correction and may increase the overall cost.

EESG is the regular synchronous generator equipped with field winding which is excited by a DC source. ENERCON of Germany introduced variable speed, direct drive (no gearbox) EESG as an alternative to a conventional wind technology solution. It is widely accepted as a mature technology, but the direct drive's global market share has never exceeded roughly 10%–15%, but the number of new entrants is growing rapidly (Aarti Gupta *et al.*,2012). In EESG, the excitation can be varied and hence the output voltage of the wind-driven EESG can be controlled in terms of amplitude and frequency during fluctuating wind. Moreover, permanent magnets are not required reducing the cost of the system drastically. Thus, to increase the global market share of EESG, a new controllable power inverter strategy is implemented.

The DC link voltage is the most representative and relevant measurement because it shows the robustness of the converter system during voltage reduction on the mains. The capability to continue stable supply during line disturbances will strongly depend on the dynamics of the DC link. This paper focuses mainly on maintaining constant DC link voltage.

MPPT extracts maximum possible power from the available wind power (Jogendra Singh Thongam, *et al.*, 2011). The amount of power output from a WECS depends upon the accuracy with which the peak power points are tracked by the MPPT controller of the WECS control system irrespective of the type of generator used. The MPPT algorithm proposed in Kesraoui, *et al.*, (2011) senses the rectified voltage (V_{DC}) alone and controls the same used here to control the dc-dc boost converter. The DC link voltage is maintained constant under varied wind speeds with this control.

Current control in VSC forces and the IGBT's to switch only when it is necessary to keep on tracking the reference of the current. The adaptive hysteresis current control in (Murat Kale *et al.*, 2005) is applied to control the VSC in this system and the DC link voltage is maintained constant under transient grid currents with this control.

Under fault condition, the DC-link circuit of the WECS with AC-DC-AC converter system experiences over-voltage. Thus, stable operation of the grid and WECS is important. During a grid side fault, depending on the severity of the voltage sag, the grid side VSC injects an appropriate voltage to compensate for any balanced or unbalanced sag and establishes a stable operating point for the generator. The capability of the WECS in enhancing voltage stability is analysed by connecting it to an IEEE 5 bus system.

2. Wind energy conversion system

2.1 System configuration

Figure 1 shows the block diagram representation of the adaptive hysteresis controlled VSWT driven EESG with MPPT. The WECS consists of a pitchable wind turbine, an EESG, a passive rectifier, a MPPT controlled dc-to-dc boost converter and an adaptive hysteresis current controlled VSC.

The details of each component of the proposed WECS are given.

2.2 Wind turbine model

The performance of wind turbine is characterized by the non-dimensional curve of coefficient of performance (C_p), as a function of tip-speed ratio λ. C_p as a function of λ is expressed by equation (1) and it is shown in Figure 2.

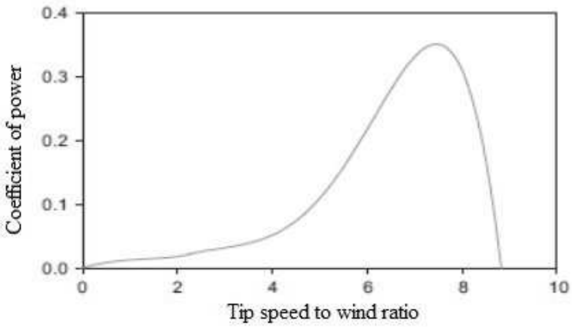

Figure 2: Cp versus λ characteristic

$$C_p(\lambda) = 0.043 - 0.108\lambda + 0.146\lambda^2 - 0.0602\lambda^3 + 0.0104\lambda^4 - 0.0006\lambda^5 \quad (1)$$

The tip-speed ratio is given by the expression:

$$\lambda = \frac{R\varpi_m}{V_w} \quad (2)$$

where R is the radius of the wind turbine rotor in m, ϖ_m is the angular velocity of the rotor in rad/sec. and V_w is the velocity of the wind in m/s.

The output power of the wind turbine P_t is calculated using equation (3) as:

$$Pt = 0.5\ Cp\ (\lambda)\ AV_w^3 \quad (3)$$

where A is the swept area of wind turbine rotor. It

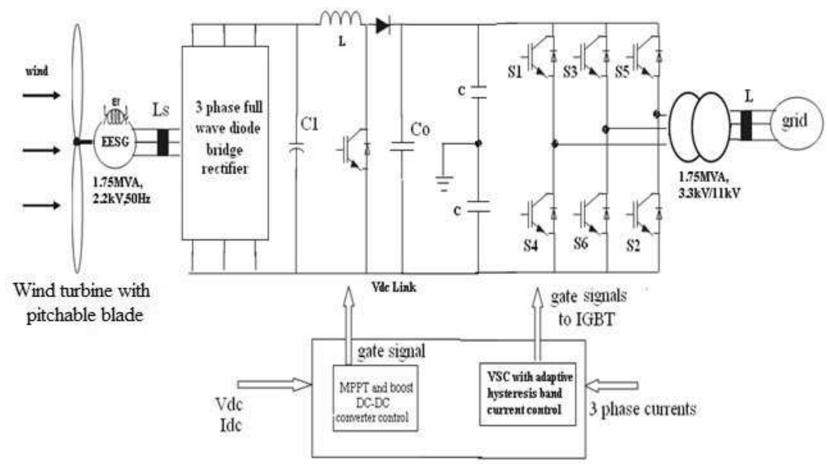

Figure 1: Schematic diagram of the adaptive hysteresis controlled VSWT driven EESG with MPPT

can be observed from Figure 2 that C_p is maximum when λ is equal to 7.5. In general,

$$P_t = T_t \varpi_m \tag{4}$$

Combining equations 1, 3 and 4, the expression for torque T_t developed by the wind turbine is written as:

$$Tt = 0.5 \, r \, A \, R \frac{C_p(\lambda)}{\lambda} \, V_w{}^2$$

The power extracted from the wind is maximized when the power coefficient C_p is at its maximum. This occurs at a defined value of the tip speed ratio. Hence, for each wind speed; there is an optimum rotor speed where maximum power is extracted from the wind. Therefore, if the wind speed is assumed to be constant, the value of C_p depends on the wind turbine rotor speed. Thus, by controlling the rotor speed, the power output of the turbine is controlled.

2.3 EESG and rectifier

The electric power generated by EESG is given by:

$$Pe = V \, I_a \tag{6}$$

where V is the generator voltage and Ia is the generator current.

For an ideal system, equations (4) and (6) can be equated.

$$Tt \, \omega_m = V \, I_a \tag{7}$$

$$I_a = \frac{V - E}{R_a} \tag{8}$$

where E is the induced voltage in the armature and R_a is the stator resistance.

Using equations (1) to (8), P_e is expressed as:

$$P_e = \frac{\omega_m \, k \, I_f}{R_a} \left(V - k \, I_f \omega_e \right) \tag{9}$$

where I_f is the field current, ω_e is the electrical angular speed and V is the generator phase voltage.

The output voltage of EESG is rectified using a three-phase passive bridge rectifier. For a diode rectifier, the dc output voltage V_{DC} is proportional to the generator phase voltage V. Therefore, equation (9) becomes

$$P_e = \frac{\omega_m \, k \, I_f}{R_a} \left(V_{DC} - k \, I_f \omega_e \right) \tag{10}$$

Figures 3a, 3b and 3c are the circuit diagrams provided to illustrate all the parameters of EESG given in Table 2 with respect to d-axis and q-axis.

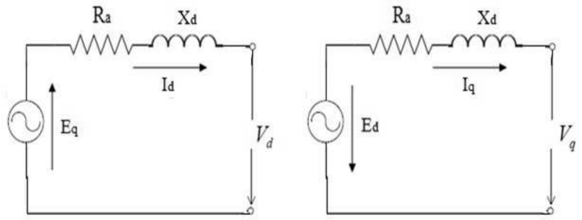

Figure 3a: Equivalent circuit of the EESG at steady state

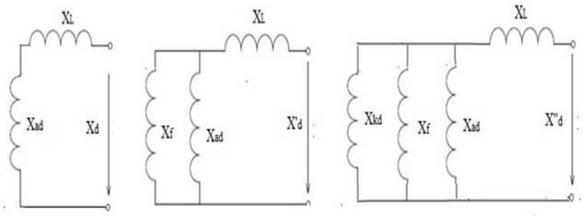

Figure 3b: Equivalent reactance for d-axis of EESG

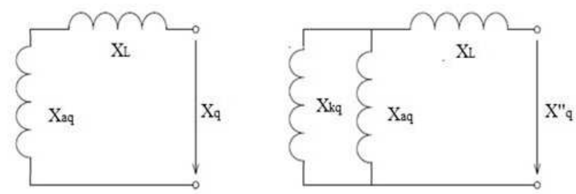

Figure 3c: Equivalent reactance for q-axis of EESG

Figure 3a shows the equivalent circuit of the EESG at steady state. From this circuit, V and I_a can be represented with respect to d-axis and q –axis as:

$$V_d = R_a I_d + X_d I_d - E_q \tag{11}$$

$$V_q = R_a I_q + X_q I_q + E_d \tag{12}$$

$$V = Vd + Vq \tag{13}$$

$$I_a = I_d + I_q \tag{14}$$

where V_d is the equivalent d-axis stator voltages, V_q is the equivalent q-axis stator voltages, R_a is stator phase resistance, I_d is the d-axis equivalent stator currents, I_q is the q-axis equivalent stator currents, I_a is the rated rms line current, X_d is the synchronous reactance for the d-axis, X_q is the synchronous reactance for the q-axis, E_d is the induced voltage by d-axis flux and E_q is the induced voltage by q-axis flux. Figure 3(b) shows the equivalent reactance for d-axis of EESG.

$$X_d = X_{ad} + X_L \tag{15}$$

$$X'_d = \frac{X_{ad} X_f}{X_{ad} + X_f} + X_L \tag{16}$$

$$X''_d = X_L + \frac{X_{ad} X_f \, X_{kd}}{X_{ad} X_f + X_{kd} \, X_f + X_{ad} X_{kd}} \tag{17}$$

where X'_d is the d-axis transient reactance, X''_d is the *d-axis* sub-transient reactance, X_{ad} is the fictitious reactance, X_L is the true reactance associated with flux leakage around the stator winding, X_f is the leakage reactance of the field winding and X_{kd} is the *d-axis* leakage reactance of damper winding(s).

Figure 3(c) shows the equivalent reactance for q-axis of EESG. If the armature MMF is aligned along quadrature axis, the only currents preventing the armature reaction flux from passing through the rotor iron are currents induced in q-axis part of the damper winding, because field winding is placed in the direct axis only. Due to this fact, it may be assumed, that q-axis transient reactance equals magnetizing reactance and only two equivalent reactances are defined as:

$$X_q = X_{aq} + X_L \tag{18}$$

$$X''_q = X_L + \frac{X_{aq}\,X_{kq}}{X_{aq}+X_{kq}} \tag{19}$$

where X''_q is the q-axis sub-transient reactance, X_{aq} is the fictitious reactance for the q-axis and X_{kq} is the q-axis leakage reactance of damper winding(s).

2.4 DC-DC Boost converter

The EESG is not capable of generating a constant high voltage at low speed. Therefore, a dc-dc boost converter must be used to raise the voltage of the diode rectifier. A capacitor C1 is connected across the rectifier to lessen the variation in the rectified AC output voltage waveform from the bridge.

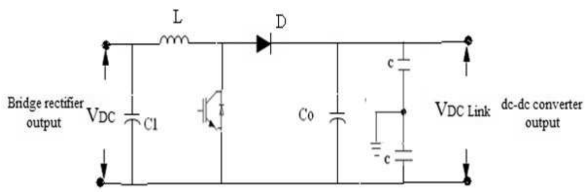

Figure 3d: DC-DC converter circuit

Figure 3(d) is an accompanying figure of Table 3, which shows the arrangement of the converter circuit, and items such as C1, capacitors, and L.

2.5 Voltage source converter

The VSC can act both as an inverter and as a rectifier. The VSC requires a minimum dc link voltage in order to operate, and here a DC-DC boost converter is introduced to increase the voltage level for the VSC. Variable voltage and frequency supply is invariably obtained from the three-phase VSC. Adaptive hysteresis type modulation is used to obtain variable voltage and frequency supply. Adaptive hysteresis current control in VSC forces and the IGBT's to switch only when it is necessary to keep on tracking the reference of the current.

3. Proposed control strategies

3.1 MPPT Control in DC-DC Boost converter

Maximum power occurs when

$$\frac{dP_e}{dV_{DC}} = 0 \tag{20}$$

The control system makes use of the fact that the generated voltage and V_{DC} depend upon the speed of the turbine. Therefore, instead of sensing the turbine speed, it senses the V_{DC} and tries to control the same. The set point for this voltage is not constant. This is because the wind speed is varying every now and then which causes the optimum turbine speed to vary frequently. The set point is floating and has to be decided by a trial and error method. The method is called Peak seeking. Figure 4 shows the step and search control strategy to track maximum power.

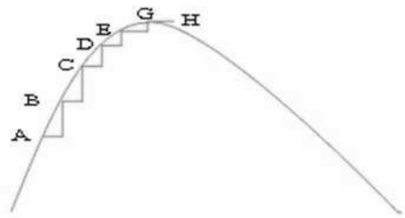

Figure 4: Step and search control strategy to track maximum power

The strategy is to start with any arbitrary set point (A) i.e. reference dc voltage and check the output dc power. Then give a small increment to the set point. Again check the output at point B. If the output has increased, give an additional increment and check the output once again. Incrementing the set point through small steps should be continued till the stage (H) when the increment does not yield a favourable result. At this stage, a small decrement to the set point should be given. The set point will be moving back and forth around the optimum value. Thus, the power output could be maximized. In this method, after giving increment to the set point, both the power output as well as the voltage level has to be checked. Four possibilities arise:

- Power increased – voltage increased
- Power increased – voltage decreased
- Power decreased – voltage increased
- Power decreased – voltage decreased

Only when power output and the voltage are increased (case 1), the set point has to be incremented. If the wind speed changes from one value to another, the turbine is not being operated at the maximum power point at the new value. The MPPT controller has to search for the new maximum power point for the new wind speed.

Thus, depending upon the MPPT controller output, the dc-dc boost converter switch operates and maintains a constant V_{DC} link across the capacitor Co.

3.2 Adaptive hysteresis current control of VSC

Figure 5 illustrates the concept of adaptive hysteresis current control. The adaptive hysteresis band current control of three phase grid connected VSC and its working as explained in Murat Kale, *et al.*, (2005) and is considered here.

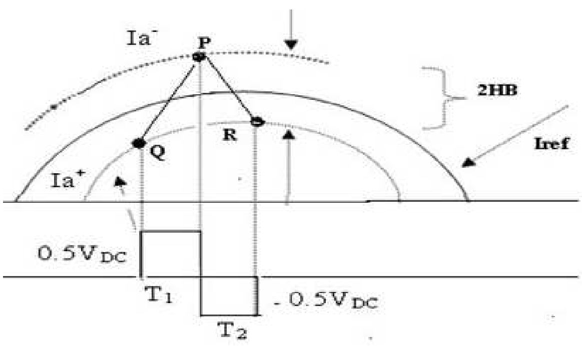

Figure 5: Adaptive hysteresis current controller concept

The adaptive hysteresis band current controller adjusts the hysteresis band width, according to the measured line current of the grid connected inverter. Let I_{ref} be the reference line current and I_{actual} be the actual line current of the grid connected inverter. The error signal E can be written in equation (12) as:

$$E = I - I_{ref} \tag{21}$$

When the measured current I_a of phase A tends to cross the lower hysteresis band at point 1, then switch S_1 is switched ON. When this touches the upper band at point P, switch S4 is switched ON. The expression for adaptive hysteresis bandwidth is derived as:

$$dI_a^{+} = \frac{1}{L}(0.5\,V_{DC} - V_a) \tag{22}$$

$$dI_a^{-} = -\frac{1}{L}(0.5\,V_{DC} + V_a) \tag{23}$$

where L is the line inductance, V_a is the grid voltage per phase and V_{DC} be the DC link voltage.

From Figure 4 we obtain:

$$\frac{dI_a^{+}}{dt}T_1 - \frac{dI_{aref}}{dt}T_1 = 2HB_a \tag{24}$$

$$\frac{dI_a^{-}}{dt}T_2 - \frac{dI_{aref}}{dt}T_1 = 2HB_a \tag{25}$$

$$T_c = \frac{1}{f_c} = T_1 + T_2 \tag{26}$$

where T_1 and T_2 are the respective switching intervals and f_c is the switching frequency. Simplifying the equations, the hysteresis bandwidth (HB) is obtained as:

$$HB_a = \frac{0.125V_{DC}}{f_c\,L}\left[1 - \frac{4L^2}{V_{DC}^{\,2}}\left(\frac{V_a}{L} + m\right)^2\right] \tag{27}$$

where f_c is modulation frequency, $m = dI_{aref}/dt$ is the slope of command current wave. The profile of HB_b and HB_c are the same as HB_a but have phase difference. According to (dI_{aref}/dt) and V_{DC} voltage, the hysteresis bandwidth is changed to minimize the influence of current distortion on the modulated waveform. Thus, the switching signals for the VSC are generated by the adaptive hysteresis band current controller.

4. Simulation results

Simulation of the proposed utility scale variable speed WECS with EESG and VSC with adaptive hysteresis band current control technique in tracking maximum power has been carried out using Matlab/Simulink. A wind turbine of 1.5 MW rating has been connected to the 1.75MVA, 2.2kV EESG. The rating of the inverter is 1.3 MVA.

4.1 Parameters of proposed system

Table 1 shows the parameters of the simulated wind turbine.

Table 1: Parameters of wind turbine model

Rating	*1.5MW*
Blade radius	38m
No. of Blades	3
Air density	0.55kg/m^3
Rated wind speed	12.4 m/sec.
Rated speed	3.07rad/sec.
Cut-in speed	4m/sec.
Cut-out speed	25m/sec.
Blade pitch angle	0^0 at 12m/sec. and 4/0.7 degree/sec. at 14m/sec.
Inertia constant of turbine	3.5925 sec.

Inertia constant of the wind turbine mentioned in Table 1 is defined as the kinetic energy stored in the rotor at rated speed divided by the VA base. The most significant component in wind turbine dynamics is the turbine inertia H_{turb}, due to the blade length and weight. It is given as:

$$H_{turb} = \frac{E}{S} = \frac{0.5J\,\omega_m^{\,2}}{S} \tag{28}$$

where E is the **e**nergy stored in rotor mass, S is the VA base, J is rotating objective inertia and ω_m is the mechanical angular velocity of rotor. The performance of wind turbines during transient situations is strongly influenced by this inertia constant.

Basic parameters used for the direct-drive generator model are given in Table 2.

Table 2: Parameters of the EESG

Rating	*1.75MVA*
Rated RMS line to neutral voltage V	1.269kV
Rated RMS line current I_a	0.459kA
Number of poles p	4
Base angular frequency	171.98rad/sec.
Inertia constant of generator H	0.3925 sec.
Stator resistance R_a	0.003 Ω
d-axis reactance X_d	1.305 p.u
d-axis transient reactance X'_d	0.296 p.u
d-axis sub-transient reactance X''_d	0.252 p.u
q-axis reactance X_q	0.474 p.u
q-axis sub-transient reactance X''_q	0.243 p.u

Table 3 shows data used for the dc-dc converter of the VSWT.

Table 3: Converter parameters

Low voltage side capacitor C1	300 μF
High voltage side capacitors	1800 μF each
Inductor L	200mH
Switching frequency	20kHz

4.2 Effect of pitch control

Simulation results are taken for two wind speeds 12 and 14 m/sec. At t = 10 sec., wind speed is changed from 12 to 14 m/sec and in step is shown in Figure 6.

In this work, since 12.4 m/sec. is the rated wind speed, at 12m/sec., the pitch angle need not be activated. During this period, $C_{p.max}$ is obtained as 0.44. At t=10 sec., as the wind speed is 14m/sec., which is above the rated wind speed of 12.4 m/sec., pitch control is activated. As the wind speed increases, the power generated by the wind turbine also increases. Once the maximum rating of the power converter is reached, the pitch angle is increased (directed to feather) to shed the aerodynamic power.

Here the pitch rate is chosen to be 4/0.7 degree/s. That is, the pitch angle can be ramped up at 4 degrees per second and it can be ramped down at 0.7 degrees per second.

The hysteresis rpm is chosen to be 2% of the maximum rpm. Small changes in the pitch angle can have a dramatic effect on the power output. Cp has changed to 0.39 at 14m/sec. as shown in Figure 7.

Figure 8 shows the variation of tip speed ratio with time. From this figure, it is observed that the turbine speed is well controlled to maintain an optimum tip speed ratio of 7 from 0 to 10 sec. at wind speed of 12m/sec. When wind speed is increased to 14m/sec., the optimum TSR is normally higher than the value at 12m/sec., but due to pitch control, it is kept at 7 itself. In general, three bladed wind turbines operate at a TSR of between 6 and 8, with 7 being the most widely reported value (Magdi Raghe.*et.al.,* 2011).

This indicates that the turbine speed is well controlled to maintain an optimum tip speed ratio to capture maximum energy. It shows that the MPPT controller is able to track maximum power and keep C_p of the wind turbine very close to maximum Betz' coefficient of 0.593. It is the maximum fraction of the power in a wind stream that can be extracted.

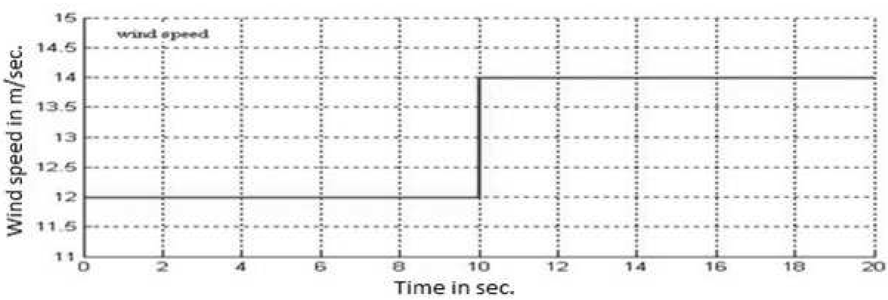

Figure 6: Wind speed profile

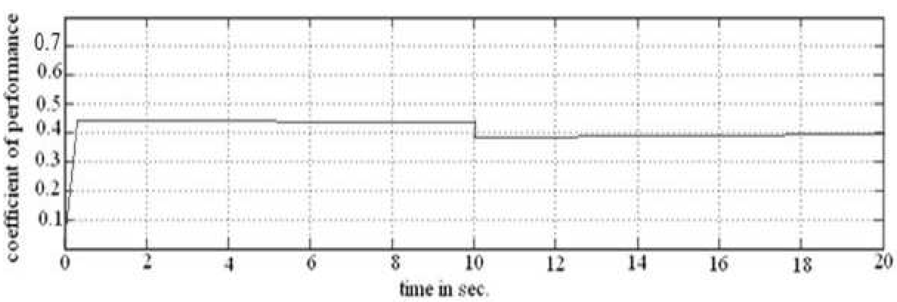

Figure 7: Coefficient of performance

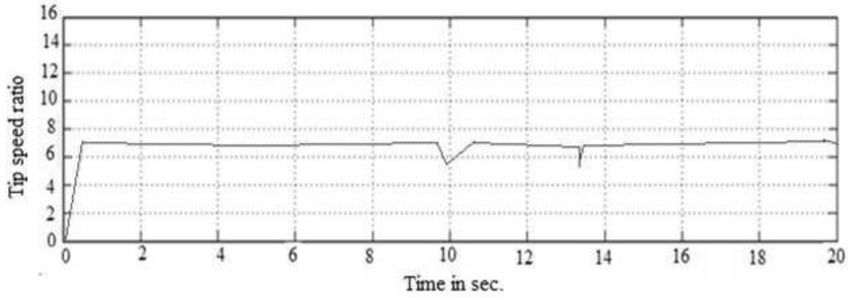

Figure 8: Tip speed ratio

4.3 Maintaining constant DC link voltage with MPPT at wind speeds of 12 m/sec. and at 14 m/sec.

Simulation results of generator phase voltage and generator phase current at 12 m/sec with zooming between 0.2 to 0.4 sec. are shown in Figure 9(a) and Figure 9(b). Figure 9(c) and Figure 9(d) show the generator phase voltage and generator phase current at 14 m/sec.

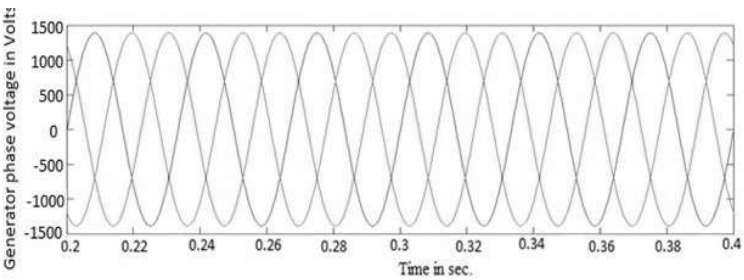

Figure 9a: Generator phase voltage at 12m/sec.

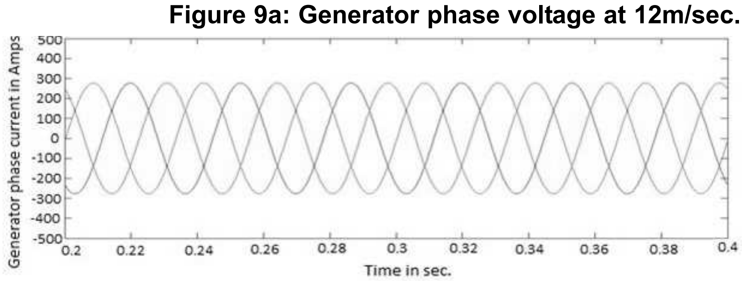

Figure 9b: Generator phase current at 12m/sec.

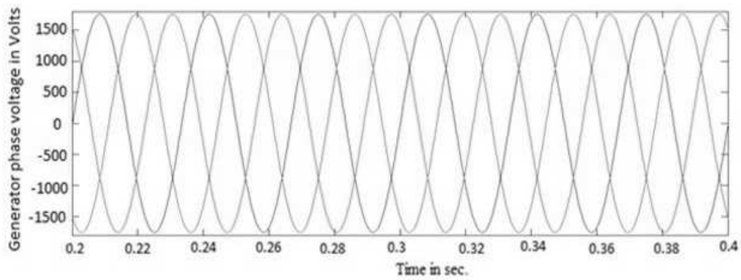

Figure 9c: Generator phase voltage at 14m/sec.

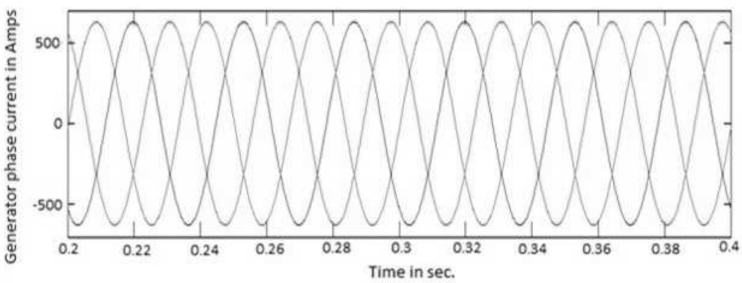

Figure 9d: Generator phase current at 14m/sec.

At 12m/sec., the generator rms phase voltage is 1.03kV and generator rms phase current is 210.49 A. At 14m/sec., the generator rms phase voltage is 1.27kV and generator rms phase current is 459.25 A. The power output at 14m/sec. is higher than that at 12m/sec. So, with increase in wind speed, the power output of the wind generator also increases.

Under both wind speed conditions, the switching signals to boost the converter are controlled with MPPT control and DC link voltage across Co is maintained constant which is shown in Figure10.

Figure 10(a) and Figure 10(c) show the DC link voltage from t= 0 to 1 sec. at 12m/sec. and 14m/sec. respectively. The simulation result of DC link voltage with zooming between 0.2 to 0.4 sec. is shown in Figure 10(b) and Figure 10(d). In the WECS with MPPT control proposed in this paper, it is possible to maintain a DC link voltage of 5.369 kV under both the wind speeds of 12m/sec. and 14m/sec.

4.4 Maintaining constant DC link voltage control with adaptive hysteresis band current controller at load currents of 50A and 130A

To analyse the dynamic response of an adaptive hysteresis current controller, the grid current is increased from *50A* to *130A* by applying load. The adaptive hysteresis current controller acts under this condition and made the load current to track the reference current command at a faster rate and prevented the grid waveforms getting distorted. Figure 11 shows the grid voltage at the point of common coupling.

Figures 12 (a, b and c) show the grid current of *50A*, inverter output phase current and corresponding hysteresis band at *50A* of grid current.

Figures 13 (a, b and c) show the grid current of 130 A, inverter output phase current and corresponding hysteresis band at 130 A of grid current.

As indicated in Figures 12(c) and 13(c), the adaptive hysteresis band varied according to the variation in load in order to maintain the constant switching frequency of operation.

Figure 14(a) and Figure 14(c) show the DC link voltage from t= 0 to 1 sec. at load conditions of 50 A and 130 A respectively. The simulation result of DC link voltage with zooming between 0.2 to 0.4

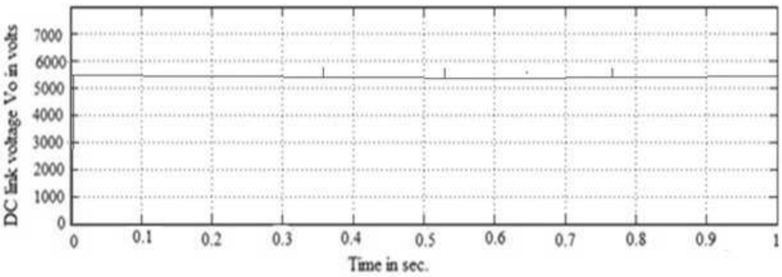

Figure 10a: DC link voltage at 12m/sec.

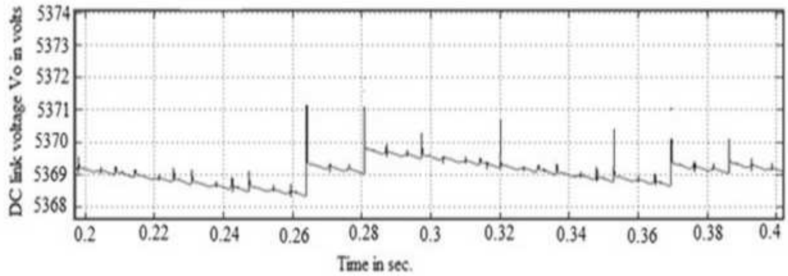

Figure 10b: DC link voltage at 12m/sec. (with zooming)

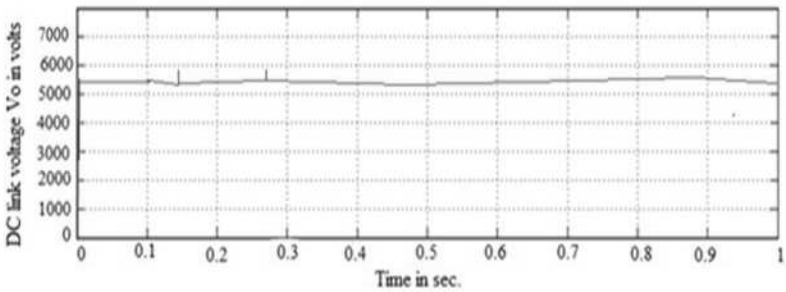

Figure 10c: DC link voltage at 14 m/sec.

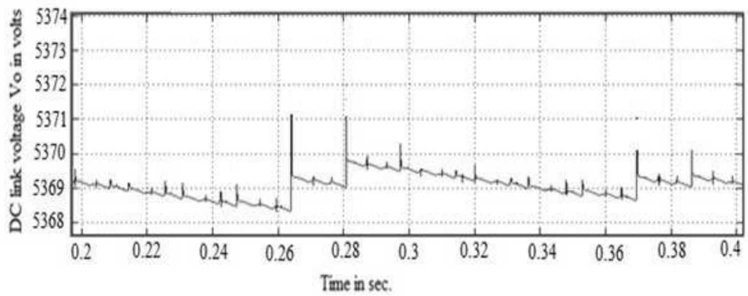

Figure 10d: DC link voltage at 14 m/sec. (with zooming)

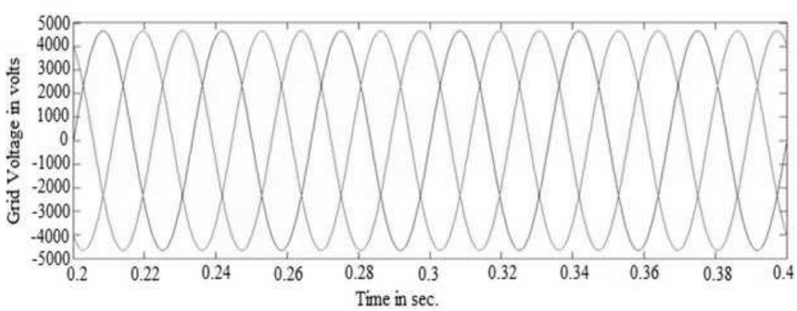

Figure 11: Grid voltage

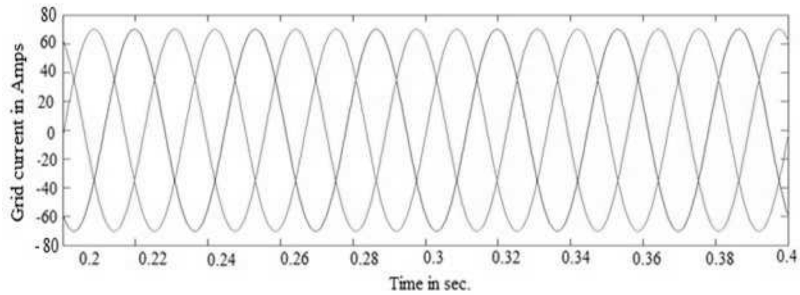

Figure 12a: Grid current

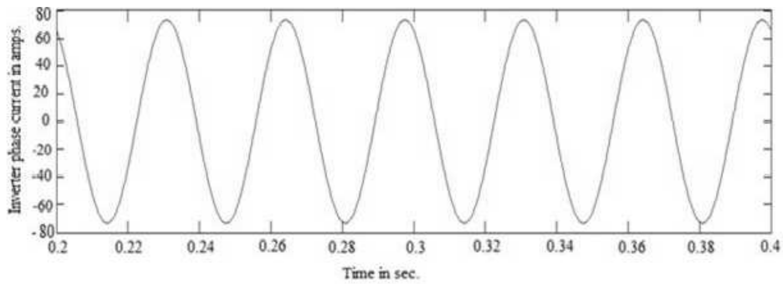

Figure 12b: Inverter output rms phase current (50A)

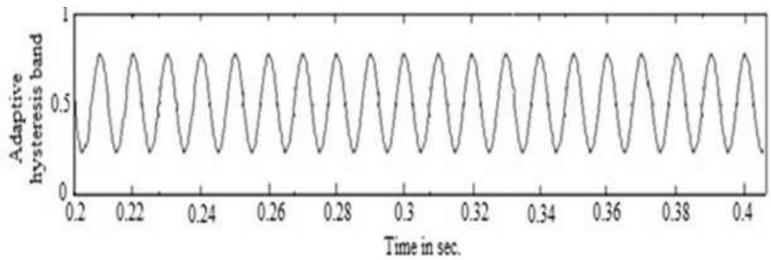

Figure 12c: Hysteresis band at 50 A

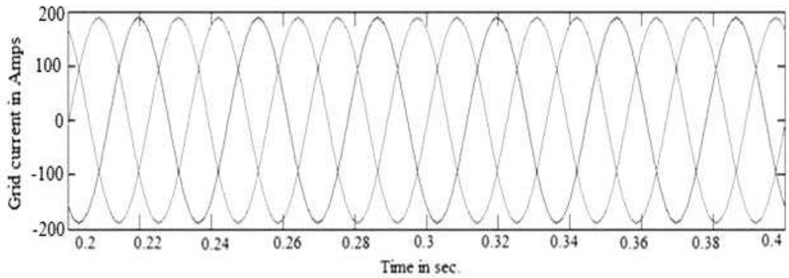

Figure 13a: Grid current

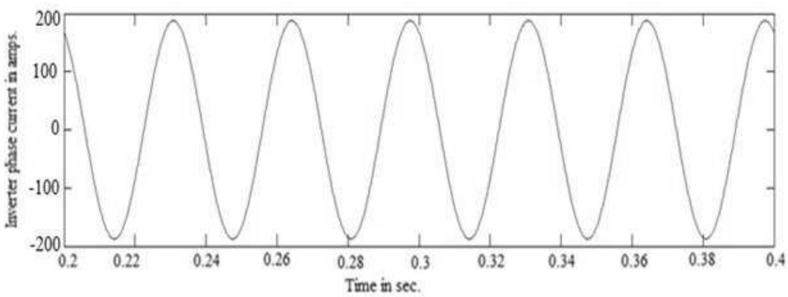

Figure 13b: Inverter output rms phase current (130A)

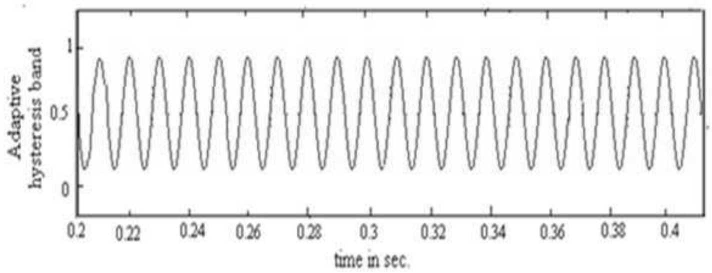

Figure 13c: Hysteresis band at 130A

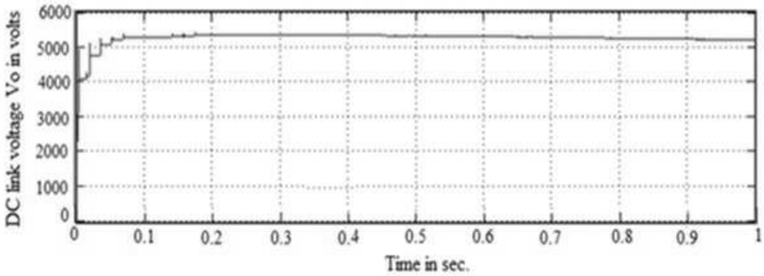

Figure 14a: DC link voltage at 50A with adaptive hysteresis current controller

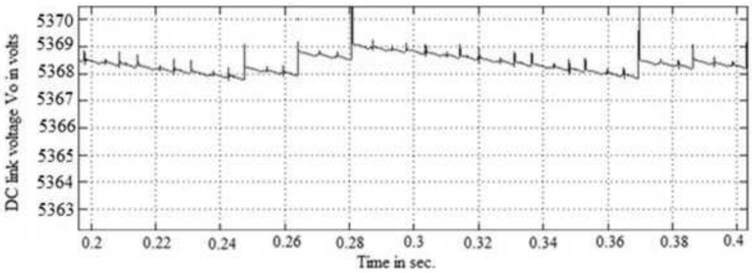

Figure 14b: DC link voltage at 50A with adaptive hysteresis current controller (with zooming)

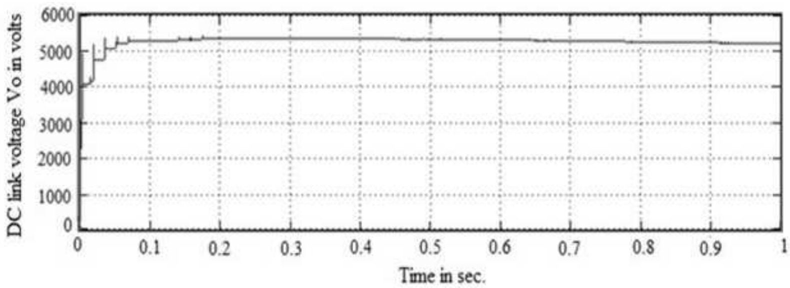

Figure 14c: DC link voltage at 130A with adaptive hysteresis current controller

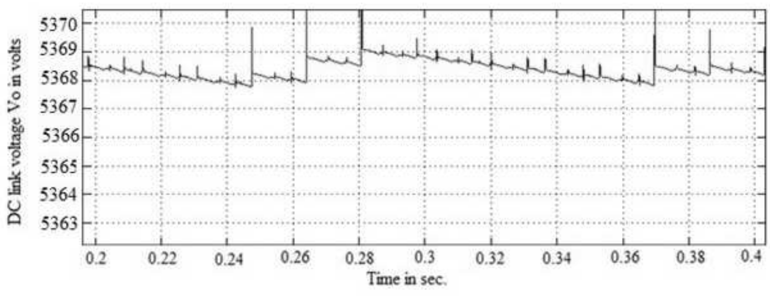

Figure 14d: DC link voltage at 130A with adaptive hysteresis current controller (with zooming)

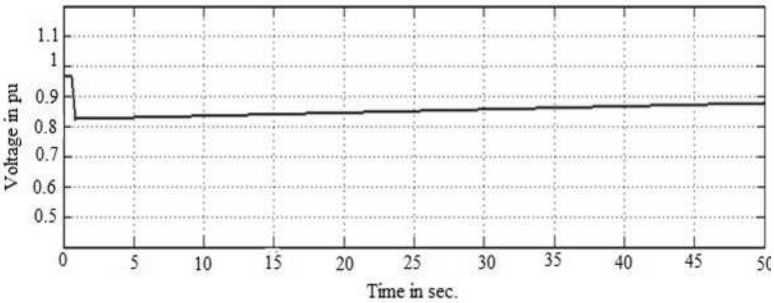

Figure 15a: Bus 3 voltage with only SCIG

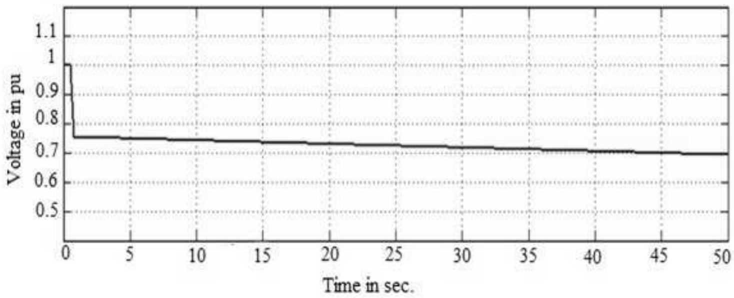

Figure 15b: Bus 4 voltage with only SCIG

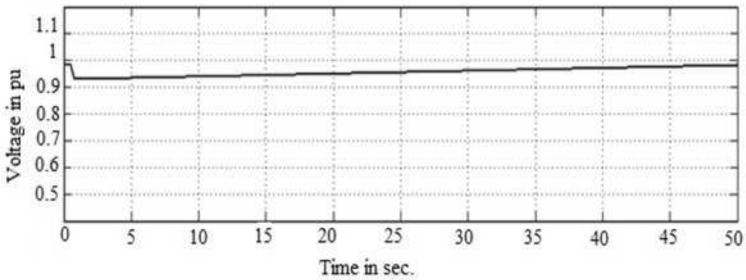

Figure 15c: Bus 3 voltage with only DFIG

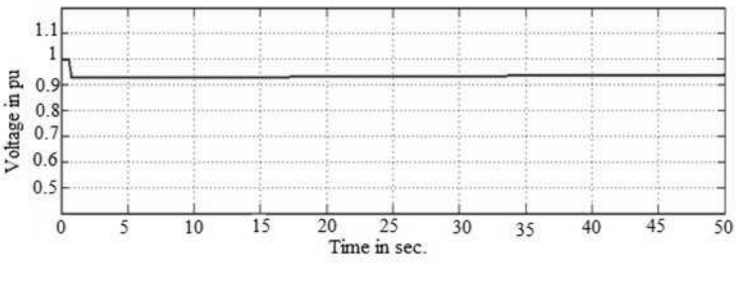

Figure 15d: Bus 4 voltage with only DFIG

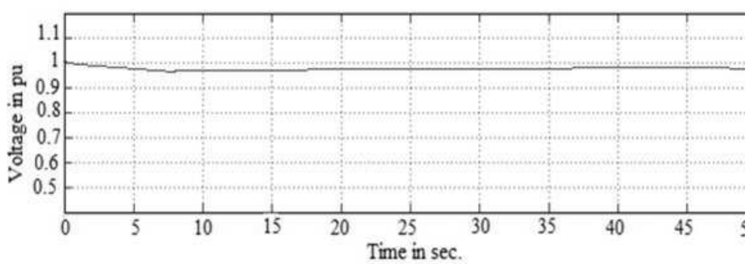

Figure15e: Bus 3 voltage with only PMSG

sec. is shown in Figure 14(b) and Figure 14(d). The WECS with adaptive hysteresis current control in VSC proposed in this paper is able to maintain DC link voltage at 5.369 kV under both the load conditions of 50 A and 130 A.

4.5 Results of voltage stability enhancement

The performance of the proposed EESG system in enhancing the voltage stability is analysed using IEEE 5 bus system. The wind generators are connected one by one and their capability to inject reactive power to enhance voltage level is analysed.

In the IEEE 5 bus system, Bus 3 is considered as the load bus, and Bus 4 as the generator bus. The IEEE 5 bus system is simulated using MATLAB software and the in-built models of SCIG, DFIG and PMSG are connected and tested.

A situation where one high-voltage transmission line gets disconnected is considered first. The changes in voltage levels in the system when connected with SCIG, DFIG, PMSG and proposed EESG are presented in Figures15 (a, b, c, d, e, f, g and h). The voltage and reactive power control is necessary in order to keep a stable output voltage to maintain the power system voltage balance.

With SCIG connected into the power system, transmission level voltage dropped and initiated a voltage collapse event as shown in Figures15 (a) and 15 (b). SCIG always consumes reactive power. The reactive power consumption of the SCIG is nearly always partly or fully compensated by a capacitor bank to achieve a power factor close to one in the steady state.

When connected with DFIG, PMSG and proposed EESG, a possible voltage collapse event is avoided. The DFIG, PMSG and EESG have complete control of reactive and active power. They utilized their reactive power injection capability to maintain transmission level voltage within limits after the grid disturbance.

The PMSG and EESG differ from DFIG in that the magnetization is provided by a permanent magnet pole system or a dc supply on the rotor, providing self-excitation property. Self-excitation allows operation at high power factors and high efficiencies. Voltage fluctuation in a PMSG is very low. Comparing the voltage levels in generator and load buses of DFIG and PMSG from Figures 15 (c), (d), (e) and (f), it is observed that, voltage fluctuation in PMSG is lesser.

Similarly, when comparing the performance of PMSG and proposed EESG from Figures 15(e), (f), (g) and (h) with respect to voltage levels during disturbance, they produced similar results. PMSG needs no power converter for field. Normally PMSG gives higher efficiency and energy yield due to very small energy losses in rotor and produce superior results than EESG. Here with proposed efficient, modified converter control in the EESG

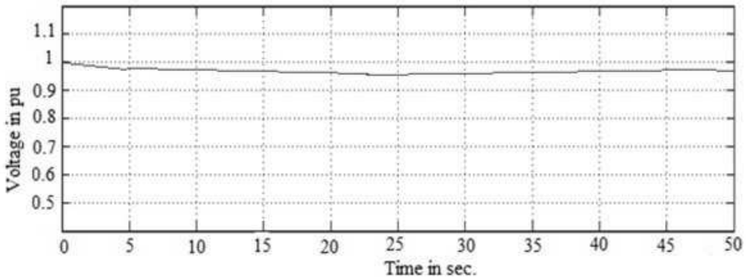

Figure15f: Bus 4 voltage with only PMSG

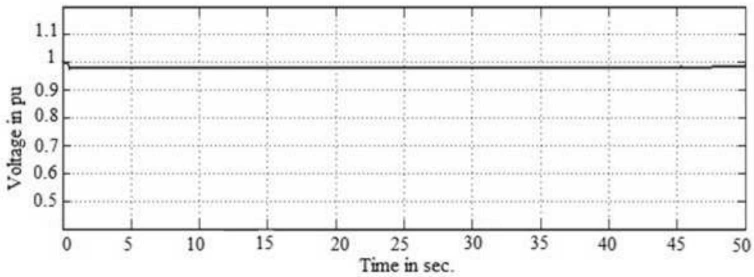

Figure 15g.Bus 3 voltage with only EESG

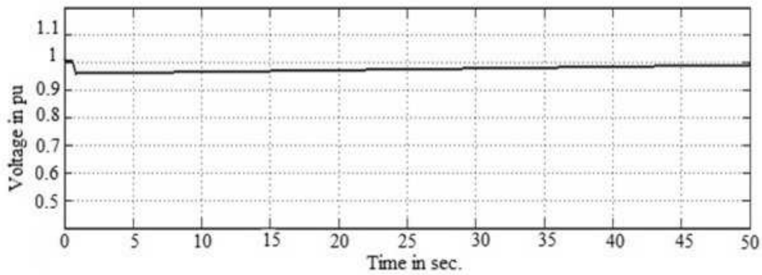

Figure 15h: Bus 4 voltage with only EESG

system, a substantial amount of reactive support is injected and the voltage collapse event is completely avoided, voltage dips are much mitigated and maintained the performance similar to PMSG.

Figures 16(a)-(d) show the reactive power injection capability of the 4 systems. From Figure 16(a), it is seen that the wind turbine system with SCIG is not capable of injecting reactive power. DFIG, PMSG and EESG are having the reactive-power injection capability which can be seen from Figures16 (b), 16(c) and (d). Compared to DFIG and PMSG, the proposed EESG has much better reactive power injection capability.

5. Conclusion

In this paper, adaptive hysteresis controlled VSWT driven EESG with MPPT is integrated into power systems and its impact on voltage stability is analysed.

It is found that with the proposed control, DC link voltage is maintained constant under varying wind speeds and different load conditions. The steady-state power transfer capacity of the transmission line is also increased.

Compared to the fixed speed SCIG, standard variable speed systems namely DFIG, PMSG and proposed EESG have more capability to improve

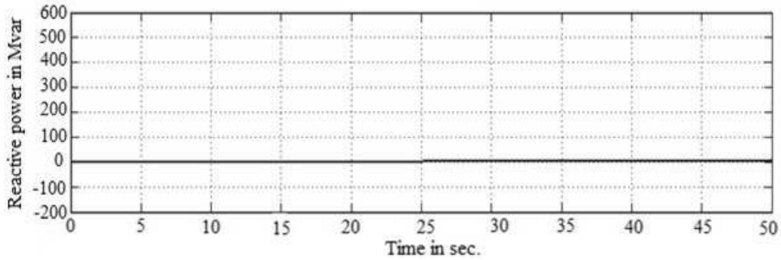

Figure 16a: Reactive power injection by SCIG

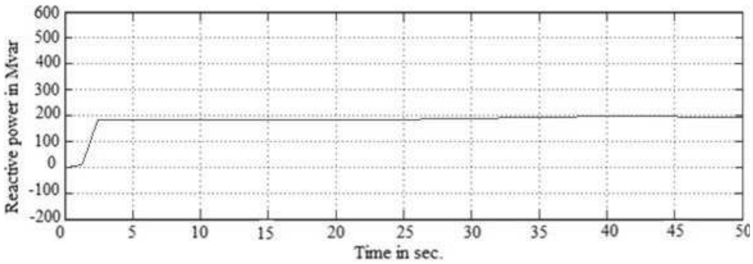

Figure 16b: Reactive power injection by DFIG

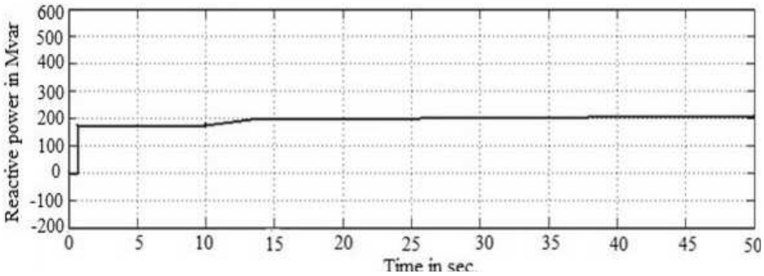

Figure 16c: Reactive power injection by PMSG

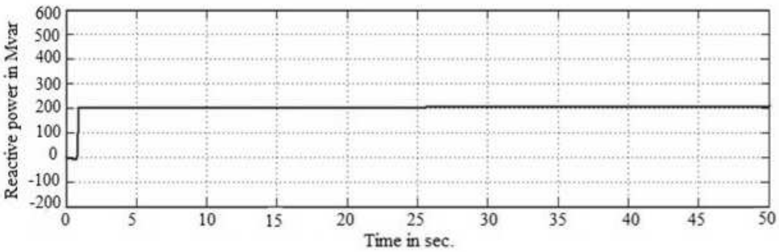

Figure 16d: Reactive power injection by EESG

long-term voltage stability by reactive power compensation. Among the variable speed systems, EESG with the proposed control strategy is found to assist the grid to delay or prevent a voltage collapse event more effectively and voltage dips are also mitigated.

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Received 19 August 2012; revised 13 April 2014

Use of hybrid solar-wind energy generation for remote area electrification in South-Eastern Nigeria

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Abstract
This paper presents simulated hybridized solar-wind generation as an alternative for rural dwellers that do not have access to a conventional grid connection. Solar and wind were used as the main sources of energy with battery storage. Each power source has a DC-DC converter to control the power flow. An axial flux permanent magnet generator, which is suitable for a location with a low wind speed, was driven by the wind turbine. By using this generator, the efficiency of the system increased since certain losses were removed. The perturbation and observation method of MPPT is used to achieve maximum power extraction from the solar panel. The hybrid system was modelled in Matlab/Simulink software. A squirrel cage induction motor was used as the electrical load to the system load. The results obtained for the proposed hybrid system indicates that it can be used as an isolated power supply. By doing so, it improves the standard of living and hence, increasing total number of citizens using energy in the country.

Keywords: hybrid solar-wind, converter, solar maximum power point tracker, induction motor, permanent magnet synchronous generator

1. Introduction

Energy is the bedrock of any nation's economic development. To meet the electrical needs, various options have been proposed. Renewable energy technology is now considered as a viable alternative to the traditionally used fossil fuel plants. The reasons being that fossil fuel is depleting and, at the same time, has negative effects globally. Such effects include air pollution, greenhouse effect, depletion of the ozone layer etc. In Nigeria today, at the rural level, where about 70% of the population lives, the percentage access to grid electricity is slightly above 18% (Sambo, 2006). This necessitates this research.

This paper presents a design simulation of a stand-alone hybrid solar-wind energy generation system for remote areas of Nsukka in south-eastern part of Nigeria located Lat. 6° 51/ N and Long. 7° 35/ E. Solar resources for the design of the system were obtained from the National Aeronautics and Space Administration (NASA) Surface Meteorology and solar energy website at a location of 6° 51' N latitude and 7° 35' E longitude, with annual average solar radiation of 4.92kWh/m^2/d (NASA, 2013). Wind-solar hybrid system consists of an emulated wind turbine generator, solar PV unit and battery storage; since is anticipated that at one time or another, there may be little or absence of both wind and solar power. During these times, the battery unit should be capable of supplying 100% of the plant's required energy. However, this will depend on the state of charge (SOC) of the battery.

In remote locations, stand-alone systems can be more cost-effective than extending a power line from the national grid (the cost of which can range from two to three million naira depending on the distance of the location from the grid lines). However, these systems are also used by people who live near the grid and wish to obtain independence from the power provider or demonstrate a commitment to non-polluting energy sources. The choice of this hybrid system stems from the fact that these two sources are complementary since sunny days are usually calm and strong winds are often accompanied by cloud and may occur at night. A combined plant, therefore, has higher availability than either individual source and so needs less storage capacity. This concept may provide power supply to the end user; which may either be any of the following: remote/rural village electrification, ideal for cell phone recipient (base) stations, residential colonies and apartments for general lighting/water pumping and street lighting (Parita *et al.,* 2012), banking sectors, hotels and business areas.

A study on the wind energy potentials for a number of Nigerian cities shows that the annual wind speed ranges from 2.32 m/s for Port Harcourt (south-south of Nigeria) to 3.89 m/s for Sokoto (north-north part of Nigeria) (Ajao *et al.,* 2011). From the research work of Ojosu and Salawu, (Adramola and Oyewola, 2011), the annual average wind speed for Enugu state in which Nsukka is part of is 2.1 – 3.0m/s (isovents at 10 m height). Similarly, solar energy (irradiance) availability in Nigeria through the same span – that is, from southern to northern part of Nigeria, throughout the year with reserve estimate is 3.5 – 7.0 kW/m^2/day (Sambo, 2009).

Nigeria receives 5.08 x 10^{12} kWh of energy per day from the sun and if solar energy appliances with just 5% efficiency are used to cover only 1% of the country's surface area, then 2.54 x 10^6 MWh of electrical energy can be obtained from solar energy (Chiemeka and Chineke, 2009). With this information, hybrid solar-wind generation should work out very well in the south-eastern part of Nigeria.

2. System components

2.1 Photovoltaic systems

A photovoltaic system is commonly modelled using the Shockley diode principles, which can be found in the literature. The model of the solar cell can be realized by an equivalent circuit that consists of a current source in parallel with diode as shown in Figure 1.

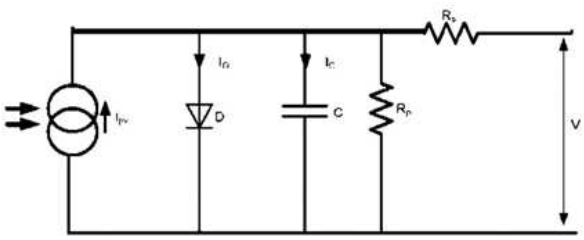

Figure 1: Equivalent circuit of solar cell

From Figure 1, the P-N junction has a certain depletion layer capacitance, which is typically neglected for modelling solar cells, therefore I_c is zero. Hence, these equations:

$$I_D = I_o\left(e^{\frac{qV}{kT}} - 1\right) \quad (1)$$

$$I_{sh} = ((V + IR_s)/ R_s) \quad (2)$$

$$I = I_{pv} - I_D - I_{sh} \quad (3)$$

$$I = I_{pv} - I_o\left(e^{\frac{qV}{kT}} - 1\right) - \frac{V+IR_S}{R_S} \quad (4)$$

$$V = \frac{kT}{q}\ln\left(1 - \frac{I - I_{pv}}{I_o}\right) \quad (5)$$

$$P_{wind} = \frac{1}{2}\rho A V^3 C_p(\lambda, \theta) \quad (6)$$

where I : Solar cell current (A); I_{pv} :Light generated current (A) ; I_O :Diode saturation current (A); q : Electron charge (1.6×10-19 C); K : Boltzman constant (1.38×10-23 J/K); T : Cell temperature in Kelvin(K); V : Solar cell output voltage (V); R_S : Solar cell series resistance (Ω); R_{SH}: Solar cell shunt resistance (Ω), I_D: diode current(A) and I_{sh}: short circuit current.

Equations (1) to (5) were modelled in MATLAB-SIMULINK software. The hybrid Polycrystalline PV panel with these ratings were used. Maximum power P_{max}= 150W, Maximum current I_{max} = 4.5A, short-circuit current I_{sc} = 4.75A and open-circuit voltage V_{oc} = 43.5V. Four of such panels were connected in series. The choice for this PV panel is due to its high efficiency while compared with monocrystalline or Polycrystalline alone

Figures 2 (a & b) denote the P-V and I-V characteristics of a photovoltaic system at different temperatures of 25°C and 50°C at varying solar irradiance respectively. At 50°C, there was decrease in power output due to the voltage decrease at that temperature. Similarly, current change was small whereas, the powers as well as the current increases with increase in solar irradiance.

Figure 3 shows P-V and I-V characteristics at constant temperature of 25°C with varying solar irradiance.

2.2 Wind turbine unit

This unit consists of a wind turbine model from a power system sub-library, 5kW permanent magnet sychronous generator, wind turbine driven control (which controls the generator speed via the mechanical torque of the generator), and pitch-angle controller (the pitch angle controller is active only in high wind speeds). In such circumstances, the rotor speed can no longer be controlled by increasing the generated power, as this would lead to overloading the generator and also the over speed of the turbine. Therefore, the blade pitch angle is changed in order to limit the aerodynamic efficiency of the rotor. This prevents the rotor speed from becoming too high, which would result in

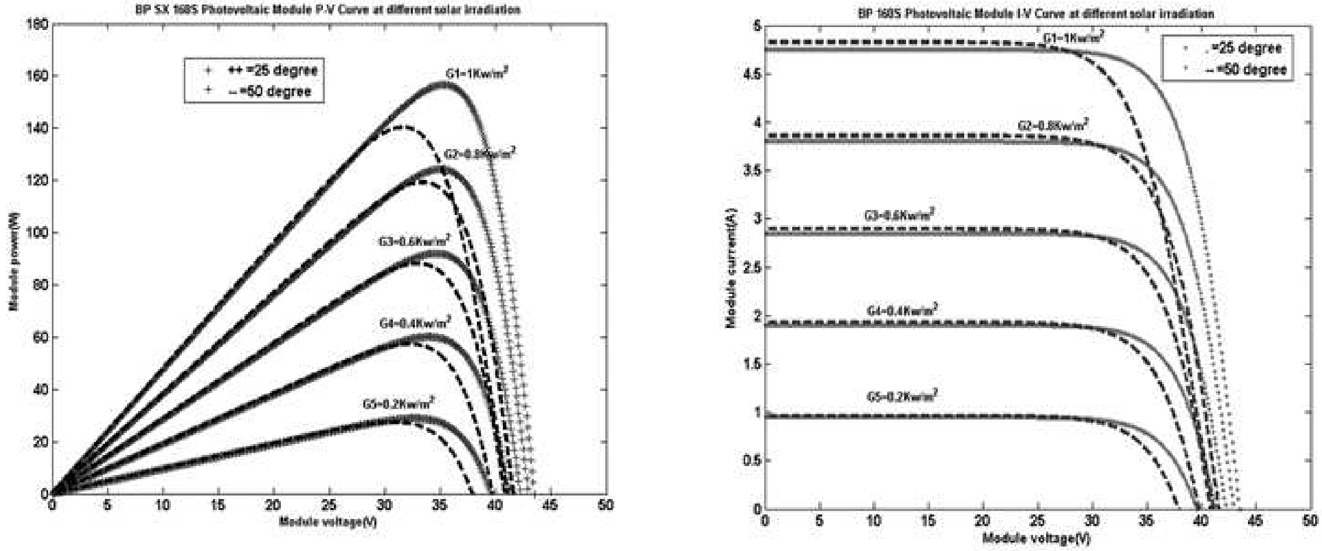

Figure 2: (a) P-V and (b) I-V characteristics at different irradiation and temperature

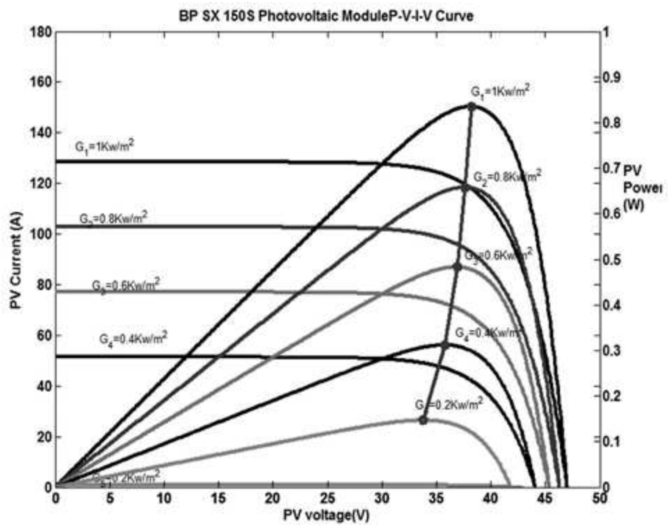

Figure 3: P-V & I-V characteristics at constant temperature of 25°C

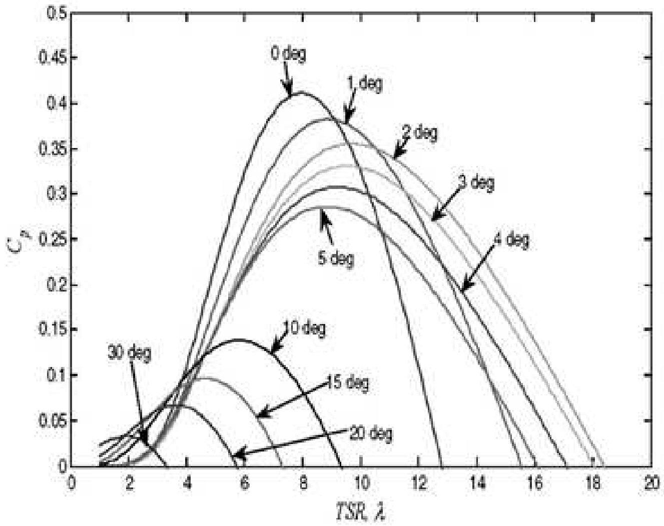

Figure 4: Cp – λ characteristics of the WECS at different pitch angles (θ)
(Ahmed et al., 2011)

mechanical damage. The optimal pitch angle is approximately zero below the nominal wind speed. A variable-speed pitch-regulated wind turbine is considered in this paper, where the pitch angle controller plays an important role.

Figure 4 shows the groups of C_p– □ curves of the wind turbine used in this study at different pitch angles (Chinchilla *et al.,* 2006). It is observed that from Figure 4 the value of C_p can be changed by changing the pitch angle ($\boldsymbol{\theta}$). In other words, the output power of the wind turbine can be regulated by pitch angle control.

In analysing the wind power P_{wind} (in watts) extracted from wind, the following equations were obtained:

$$P_{wind} = \frac{1}{2}\rho A V^3 C_p(\lambda, \theta) \tag{6}$$

where ρ is the air density (1.22kg/m^3), A is the area swept by the rotor blades in m^2, and V is the wind velocity in m/s. C_p is called the power coefficient or the rotor efficiency; where the theoretical maximum value is 0.593 (Anandavel *et al.,* 2005) and is a function of tip speed ratio (TSR or λ) and pitch angle (θ).

C_p is represented as a function of the tip speed ratio λ given by Monica *et al.* (2006) as:

$$\lambda = \frac{R}{V}\omega_t \tag{7}$$

where ω_t is the turbine speed.

It is important to note that the aerodynamic efficiency is maximized at the optimum tip speed ratio. The torque value obtained by dividing the turbine power by turbine speed is obtained as follows:

$$T_t(V, \omega_t) = \frac{1}{2}\pi\rho R^2 C_t(\lambda) V^3 \quad (8)$$

Where C_t (λ) is the torque co-efficient of the turbine given by (9) and area swept by the blades is given by this; $A = \pi R^2$

$$C_t(\lambda) = \frac{C_p(\lambda)}{\lambda} \quad (9)$$

The power co-efficient C_p is given by Anandavel *et al.* (2005) as shown in equation (10):

$$C_p(\lambda) = \left(\frac{116}{\lambda_1} - (0.4 * \theta) - 5\right) * 0.3e^{\frac{-16.5}{\lambda_1}} \quad (10)$$

Where $\lambda_1 = \frac{1}{\left(\frac{1}{\lambda + 0.089\theta}\right) - \frac{0.035}{\theta^3 + 1}}$

$$\lambda_1 = \frac{\frac{1}{\theta^3+1}}{(\lambda + 0.089\theta) * 0.035} \quad (11)$$

The turbine is connected to the rotor of the generator via a shaft. The turbine, shaft and generator are modelled as a single rotating mass:

$$\frac{d\omega_t}{dt} = \frac{1}{J_{total}} . (T_e + T_m) \quad (12)$$

T_e is the electromechanical torque developed by the electrical machine in N.m (when the electrical machine is operated as a generator T_e will be negative), T_m is the mechanical torque delivered by the wind turbine in N.m and *Jtotal* is the moment of inertia of the entire mechanical system in kg-m^2.

In per unit (p.u.) values equation (12) becomes:

$$\frac{dn}{dt} = \frac{1}{\tau_m} . (T_e + T_m) \quad (13)$$

Where τ_m is the time constant in sec.

Figure 5 is a pitch angle controller, which is a proportional (P) controller. Using this controller type implies that the rotor speed is allowed to exceed its nominal value by an amount that depends on the value chosen for the constant K_p.

The choice of direct driven PMSG is due to the fact that it has no gearbox which produces losses due to friction; and hence, the frictional torque in a gearbox which leads to starting problems of such generator is avoided. Similarly, the gearbox needs oil and regular maintenance results to reduced overall system reliability. Hence, due to the higher efficiency of PMSG and the wide range of speed control in the PMSG, it stands the best option for this research work.

Almost all drive systems use the dynamic *dqo* (direct-quadrature-zero axis) model of a machine. This converts the 3 phase alternating current quantities to direct current quantities, which can be easily controlled by a simple proportional integral (PI) controller. The transformation from 3 phase variables with time varying (abc) frame to stationary dqo-frame is as defined in Figure 6 (Heier, 1998).

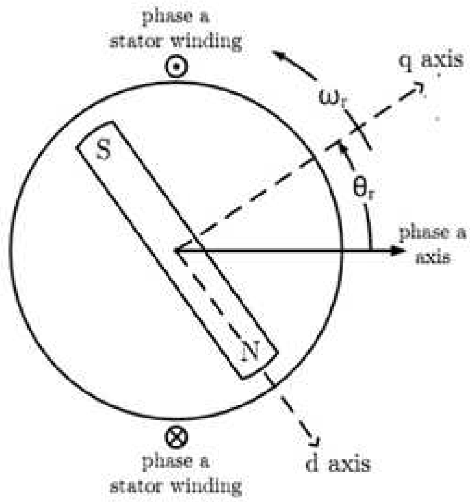

Figure 6: Synchronization for the rotor position for the park transformation
(Heier,1998)

Machine equations based on the rotor reference position are described in Equations (14) and (15) and they are marked with the subscript *'r'*.

$$V_q^r = -R_s I_q^r - L_q \frac{dI_q^r}{dt} - \omega_r L_d I_d^r + \omega_r \varphi_{pm} \quad (14)$$

$$V_d^r = -R_s I_d^r - L_d \frac{dI_q^r}{dt} + \omega_r L_q I_q^r \quad (15)$$

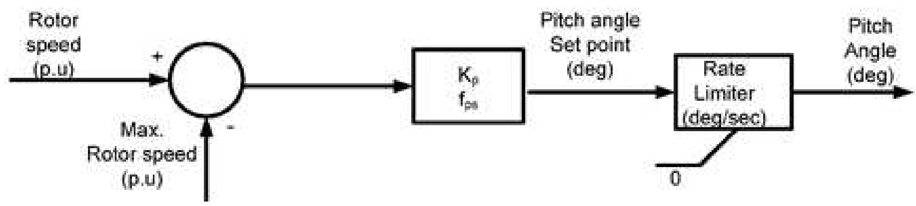

Figure 5: Pitch angle controller model; where K_p is a constant; f_{ps} is the sample frequency of the pitch angle controller

The variables R_s, L_d and L_q are the stator resistance, direct and quadrature inductance respectively of a permanent magnet synchronous generator, where $L_d = L_q = L_s$.

Figure 7 shows the equivalent circuit of the PMSG in d-q axis. The electrical torque is shown in equation (16). It should be noted that to control the electrical torque, the q-axis current can be controlled, hence the essence of (16).

$$T_e = 1.5P\varphi_{pm}I_q^r \qquad (16)$$

The back emf (E_{pm}) produced by the magnets depends on the mechanical rotational speed ϖ_m (rad/sec).

Therefore,

$$E_{pm} = \varpi_e * \varphi_{pm} \qquad (17)$$

Where ϖ_e is the electrical rotational speed (rad/sec) and φ_{pm} is the flux linkage established by the magnets in weber. Hence,

$$\varpi_e = P * \varpi_m. \qquad (18)$$

Where P is the number of pole pairs of the generator.

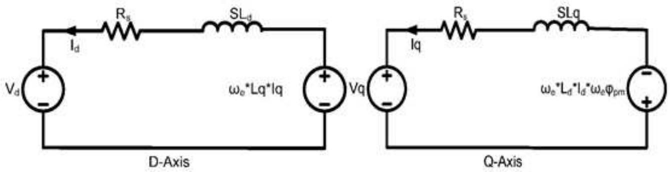

Figure 7: Equivalent circuit of PMSG in d-q reference frame

The prime mover for PMSG is a wind turbine with optimum power control and pitch angle control. The external inputs to the turbine are wind speed and rotor speed. Optimum power is obtained from the Power-Speed characteristics, which depend upon the speed of the turbine. A rotor side converter is controlled by vector control. The main objectives are for active and reactive power flow control and maximum power point tracking. The grid side converter's main objective is to regulate the DC link capacitor voltage and this converter controls the power flow between the DC bus and the AC side.

2.3 Energy storage device model

The energy storage devices are used for three purposes: energy stabilization, ride through capability and dispatchability. The energy stabilization permits the hybrid system to run at a constant stable output level with the help of the energy storage devices, even if the load fluctuates rapidly. The ride through capability is the capability of the energy storage device that provides the proper amounts of energy to the loads, when the hybrid system generation units are unavailable be it in the night or in a period of faults. There is a controller that charges or discharges the battery to fix DC link voltage.

In the analysis, the structure of the battery consists of a constant dc source, and internal capacitances and resistances shown in Figure 8.

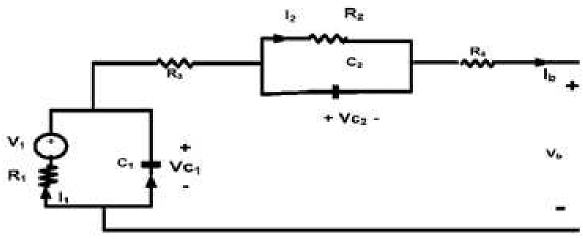

Figure 8: Battery model
Hossein (2012)

Considering Figure 8, from analysis one was able to get the following formulae

$$\begin{cases} R_1I_1 - V_1 - V_{c1} = 0 \\ R_2I_2 - V_{c2} = 0 \\ V_{c1} + V_{c2} + (R_3 + R_4)I_b + V_b = 0 \end{cases} \qquad (19)$$

$$\begin{cases} I_1 = I_b - C_1\frac{d}{dt}V_{c1} \\ I_2 = I_b - C_2\frac{d}{dt}V_{c2} \end{cases} \qquad (20)$$

$$R_1\left(I_b - C_1\frac{d}{dt}V_{c1}\right) - V_1 - V_{c1} = 0 \qquad (21)$$

$$R_2\left(I_b - C_2\frac{d}{dt}V_{c2}\right) - V_{c2} = 0 \qquad (22)$$

$$V_b = -V_{c1} - V_{c2} - (R_3 + R_4)I_b \qquad (23)$$

$$\begin{cases} R_1C_1\frac{d}{dt}V_{c1} = R_1I_1 - V_1 - V_{c1} \\ R_2C_2\frac{d}{dt}V_{c2} = R_2I_b - V_{c2} \end{cases} \qquad (24)$$

$$V_b = -V_{c1} - V_{c2} - (R_3 + R_4)I_b \qquad (25)$$

The model of the battery suitable for this project is as shown and the battery should be a deep cycle battery. This type of battery can withstand fluctuations as well as discharge slowly.

3. Proposed hybrid energy system

Wind and solar energy are converted into electricity and then sent to loads or stored in a battery bank. The topology of the hybrid energy system consists of a PV array and variable speed wind turbine, coupled to a permanent magnet synchronous generator (PMSG) with a deep cycle battery as a back-up. The two energy sources are connected in parallel to a common dc bus line through their individual DC-DC converters. The load may be dc connected to the dc bus line or may include a PWM voltage source inverter to convert the dc power into 50Hz AC supply.

The two generating sources were controlled individually, of which their output goes to the dc bus line to feed the isolating dc load or to the inverter section of the system for ac load. The use of a battery charger and its accessories were to keep the battery fully charged at a constant dc bus line voltage and also for monitoring/protection of the battery in case of over charge or over discharge. The voltage from both the wind turbine and solar panel were connected to the battery via a battery charger. This device has a regulator that allows only the required voltage that will charge the battery in to the charger. When the output of the system is not available, the battery powers the dc load or discharges to the inverter to power ac loads, through a discharge diode D_b. A battery discharge diode D_b is to prevent the battery from being charged when the charger is opened after a full charge. As depicted in the system configuration represented in Figure. 8, the V_{dc} is set to a fixed dc bus line voltage and the output dc voltage from each source is controlled independently for both generation systems (Yerra *et al.,* 2012).

3.1 Maximum power point tracker for the PV systems

The output of the PV was fed in to a boost converter before connecting it in to DC link. The essence of this is to boost PV output. The MOSFET switch of the boost converter for the PV system will be triggered by the P&O algorithm of the MPPT of the PV panel, which will be modulated by a triangular wave to get a pulse width modulated signal. This is to ensure that the maximum power of the PV system will be transferred to the load via an inverter. The P&O method of MPPT measurement senses both the voltage and current inputs from the PV panels arbitrarily, and computes the power and then increments or decrements the voltage and power. The new data is compared to the previous readings. If the power increases, the voltage is moved in the same direction as the last adjustment. This continues until the new value shows less power than the previous one. The direction is then changed to try and reach the peak power output. The algorithm is shown in Figure 10.

Similarly, the output of the PMSG was also fed into a three phase rectifier through a buck converter in that the voltage input- output ratio is controlled by a PWM to get a dc signal, which was linked up with the dc link.

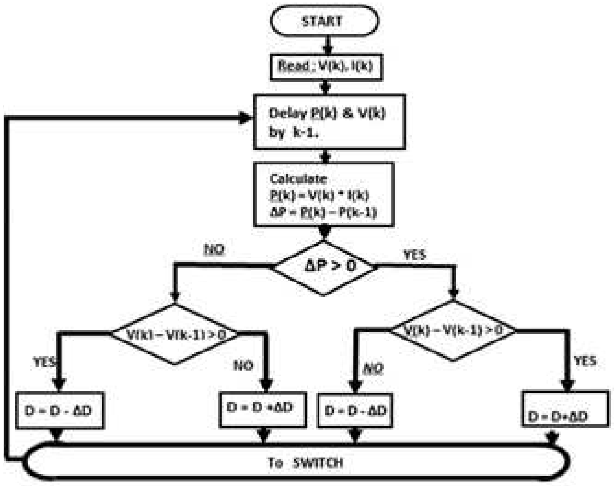

Figure 10: P&O algorithm for PV panel MPPT

However, the controller in the charger switches the battery on and off if neither the PV nor the wind turbine produces enough voltage and if both produce voltage respectively. The voltages from both sources were connected to the dc link form which it was connected through a three phase inverter.

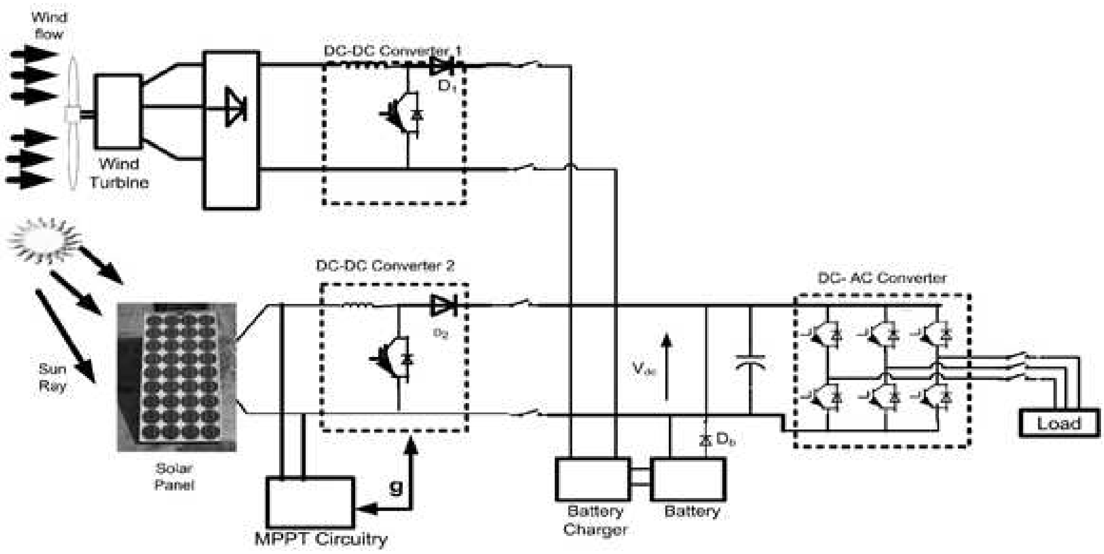

Figure 9: Diagram of the proposed hybrid solar-wind stand-alone generation

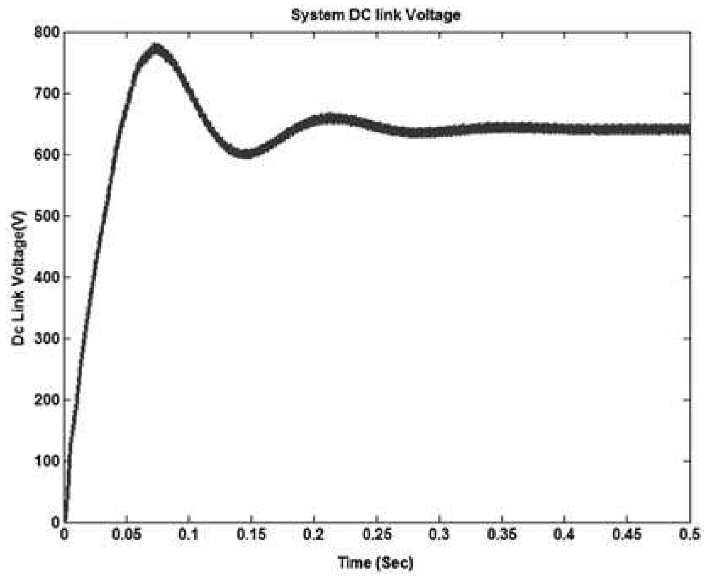

Figure 11: DC-Link voltage

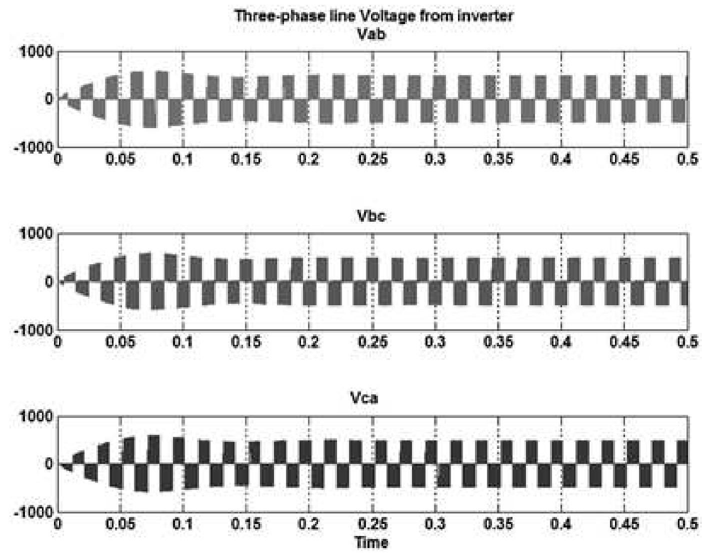

Figure 12: Line voltages from the inverter

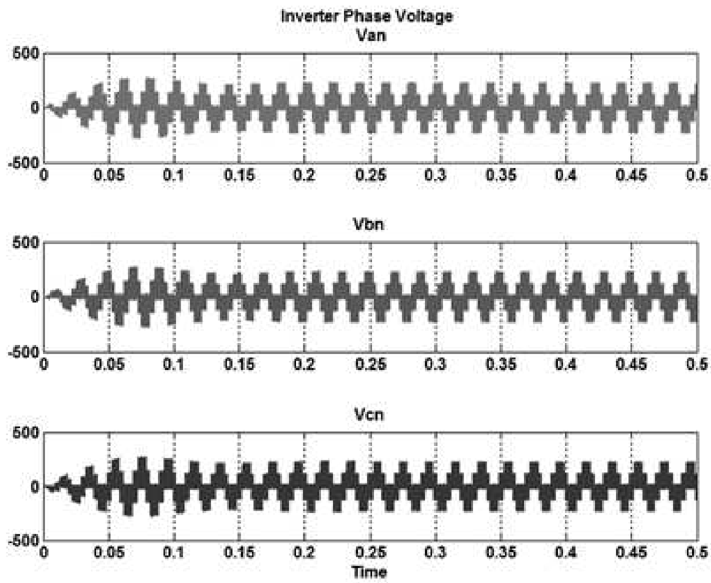

Figure 13: Inverter phase voltage

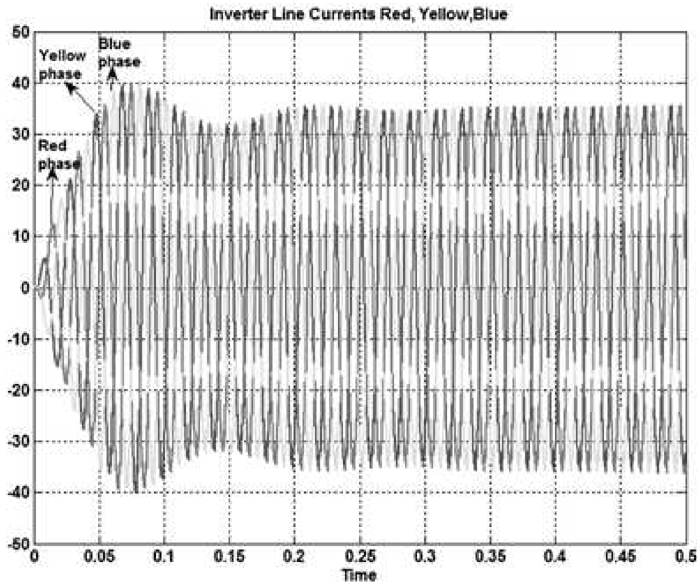

Figure 14: Line currents from inverter

4. Results of the simulations

The results of the simulations were presented asshown in Figures 11–16.

4.1 Evaluation of the results

When the wind turbine output, which is three-phase is connected via a three-phase rectifier, the output of the rectifier is connected to a dc-link together with the PV system output, the result is shown in Figure 11 and this dc-link capacitor voltage is 0.64kV. However, these dc-link capacitor voltages of the hybrid source were connected through a three-phase PWM inverter. Figure 12 shows the two-level pulse width modulated (PWM) line voltages which were used to operate a 4kW squirrel caged induction motor. Similarly, two level PWM phase voltages of 230V each of the inverter output was also generated and shown in Figure 13.

When connected via a balanced three-phase resistive load, the line current values generated are shown in Figure 14. Figure 15 indicates both the rotor and stator current of the induction motor, which after 0.012sec, the transients die down to state steady current of about 33 A. Figure 16 indicate the electromagnetic torque of the squirrel cage induction motor that the hybrid source was used to supply.

5. Conclusion

With the high demand of energy in this part of the world, this paper is presenting an alternative to be used by the remote areas in Nsukka, south-eastern

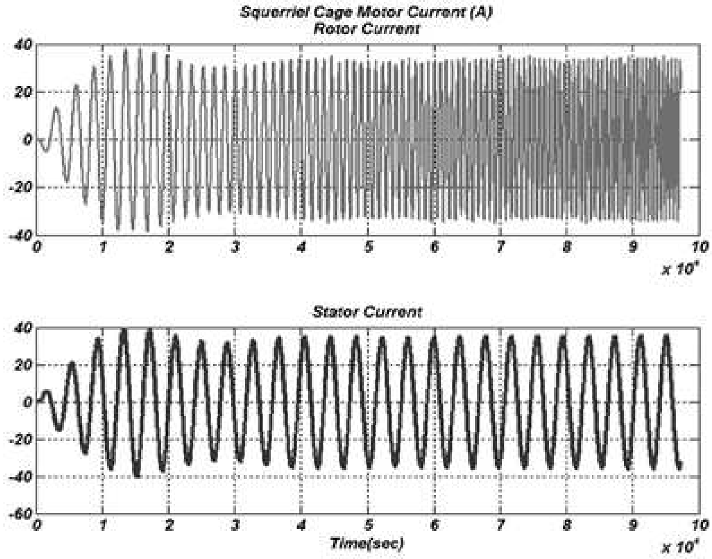

Figure 15: Output from Sq. caged IM

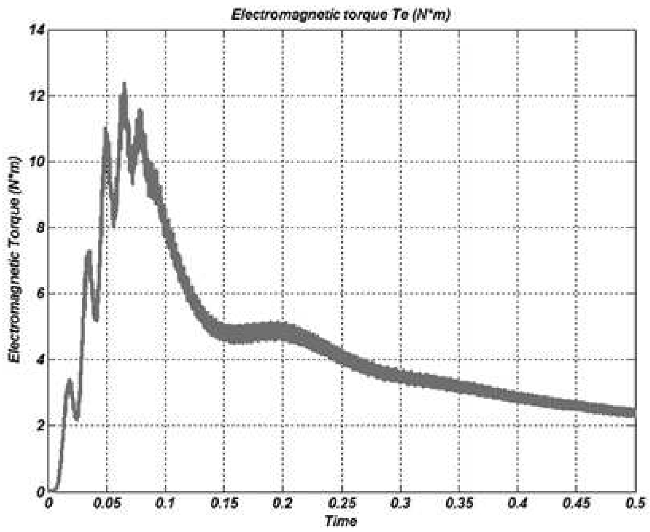

Figure 16: Electromagnetic torque of the IM

part of Nigeria. As indicated, the availability of solar irradiance and wind speed in this part of the country is good enough to make the hybrid give high yield. Similarly, from the simulation result, the paper suggests that even mobile base stations, hospitals and hotels can start to make use of hybrid solar-wind generations.

This kind of energy generation can work effectively either as a single-phase supply or three-phase supply, in which case appliances of either single or three-phase can be used effectively. From the result of the simulation, it is observed that with little increase in the capacity of the wind turbine as well as number of PV panels, many homes can be covered. Since the power obtained from wind generation adds to the power from the PV system thereby improving the quantity of power available for the masses to use; the hybridized system if implemented will boost availability of power in the area. This paper therefore appeals to government and private investors to explore this means of power generation to help ameliorate the suffering of the poor masses in this part of the country as regards to inadequate power supply.

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Received 12 June 2013; revised 30 May 2014

An analysis of the solar service provider industry in the Western Cape, South Africa

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Abstract

Scientists agree that rising electricity usage of the rapidly growing human race to improve its standard of living is negatively affecting the environment. To create a sustainable environment for future generations, renewable and environmentally friendly resources have to be exchanged for the present finite resources. In South Africa, coal plants are responsible for more than 90% of electricity production. This means that action has to be taken now to start a process of change to sustainable electricity resources.

This paper focuses on the South African solar industry. Due to the high sun radiation levels, solar technology is one of the renewable energy sources with the greatest potential. The industry is in its infancy, characterised by accelerated growth expectancy and fuelled by factors such as government subsidies, the fluctuations of fossil fuel prices and the increasing focus on economical long-term sustainability. The expected growth necessitates a focus on the market positioning of solar service providers in the Western Cape, with the aim of taking full advantage of the opportunities associated with this industry.

The main objective is to determine the current structure of the solar service provider value chain and subsequently areas of improvement to increase growth, stakeholder satisfaction and sustainability.

A literature review was conducted to address the research objective, relevant approaches and the broader electricity industry. Porter's Value Chain approach was used as a foundation for the adaptation to the solar service provider value chain. Porter's Five Forces model was also used as a secondary approach, which analysed the competitive environment of the solar service provider industry in the Western Cape.

The methodology entailed a qualitative research approach in the form of semi-structured interviews. All respondents were general managers or owners of a solar service provider, who were interviewed face to face. The research focused on the entire population of solar service providers in the Western Cape. Seventy-seven different service providers were targeted, of which 18 were interviewed. The interviews were transcribed and analysed using content and frequency analysis. To guarantee reliability, a pilot study was conducted to ensure that the respondents understood the questionnaire.

The findings show that customer service is the foremost value driver for solar service providers. This entails the actual installation of the product as well as the people skills of the installation team. As most customers only have to be served once due to the long life span of the products, marketing also plays an obvious role in attracting new customers.

The most important outcome of this paper is the determination and a better understanding of the solar service provider value chain in South Africa. The recommendations, especially with regard to marketing and service elements, could improve the performance of solar service providers. The consequence could be an increase in stakeholder satisfaction and an enhanced usage of solar energy in South Africa. Future research should focus on customers to reveal preferences and opportunities for marketing approaches.

Keywords: Porter's Value Chain approach, Porter's Five Forces model, solar service provider, South African solar industry, renewable sources of energy, South African energy industry

1. Introduction

Climate change is one of the major challenges of our time. It is scientifically proven that human action is having a negative effect on the environmental balance of our planet. The global energy sector accounts for around two-thirds in 2010 of greenhouse-gas emission[1]. In addition, most fossil fuels are becoming more expensive due to a mixture of higher demand, limited supply and carbon mission taxing (International Energy Agency, 2013a). Consequently, to decrease price volatility and increase energy security, it is important to start switching to new sources of electricity, which have the potential to contribute to sustainably cover the worlds increasing electricity demand. The Medium-Term Renewable Energy Market Report (MTRMR) from the International Energy Agency (IEA) predicts an increase by 40% of renewable energy in the next 5 years (International Energy Agency, 2013b).

The outcome of this paper will contribute to the development of South Africa's renewable energy industry by analysing the present structure of the solar service provider value chain in the Western Cape. No previous research in South Africa could be found, which focuses on this part of the market. The Western Cape was selected due to the high population of solar service providers. Further research could investigate the matter on a national scale.

The outcome could contribute to a sustainable long-term development of the downstream industry's value chain. The term 'downstream value chain' means that activities, which are closer to the customer are analysed, rather than the production site. The main focus of the paper is on solar service providers in the Western Cape, who stay in immediate contact with the customer. The service provider is the last link between the supplier and the final customer, and consequently has to handle the finished developed products of the supplier and find potential customers. The value chain approach is utilised to improve this process.

2. Research approaches to analyse the solar service provider industry

The following section provides a brief explanation of two models, namely the value chain model and Porter's Five Forces model. Both models are used to systematically analyse the solar service provider industry in the Western Cape and to identify opportunities for improvement.

2.1 The value chain approach

Every business consists of several steps in designing, producing, marketing, delivering and supporting its product or service. This approach is called 'the value chain model', as every step creates value for the potential customer (Gibbon, 2001). Value chains differ from company to company as business strategies and the internal and external environment differ (Humphrey & Schmitz, 2000). The value chain describes how the whole process from raw material to the end consumer is linked together. The process consists of primary and secondary activities (Hough, Thomson, Strickland & Gamble, 2011).

The fundamental model of Porter's value chain is illustrated in Figure 1 and contains primary and secondary activities. Primary activities are inbound logistics, operations, outbound logistics, marketing and sales, and service. Secondary activities are the firm's infrastructure, human resource management, technology and procurement (Humphrey & Schmitz, 2000).

Porter's value chain represents the basic model on which the current research is based. The primary research knowledge is collected to adapt the model to solar service providers in the Western Cape solar industry. In addition, key areas for development of the Western Cape solar service provider value chain are identified, and recommendations for improvement in the best interest of all stakeholders are presented.

The solar service provider is the last link of the industries value chain to the customer. It is a very

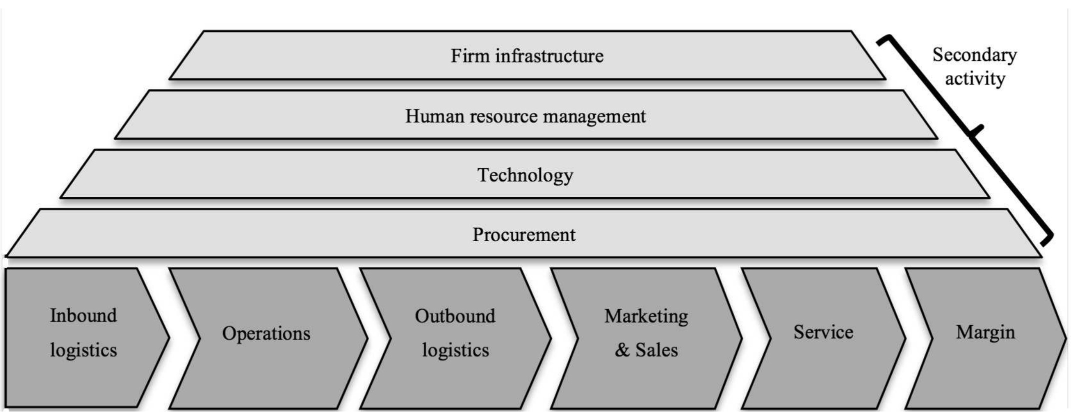

Figure 1: Porter's Value Chain
Source: Porter (1985)

fragmented segment of the value chain with very few companies that operate at national level (Donev, Van Sark, Blok & Dintchev, 2012).

2.2 Porter's Five Forces model

Porter's Five Forces of competition is by far the most powerful model to systematically diagnose the principal of competitive pressure. The model evaluates five different areas, namely rivals, new entrants, substitute products, buyers and supplier bargaining power (Porter, 2007). The model can be seen in Figure 2.

Porter's Five Forces model contributes to understanding of the renewable energy industry, and specifically the solar industry in South Africa. The knowledge of where most competitive pressure comes from assists in providing adequate recommendations in relation to future value chain adjustments (Porter, 2008). The understanding of which of the five competitive forces is stronger, assists in focusing on value chain activities interacting with this force. The improvement of these value chain activities adds more value to businesses as they improve their performance in areas most crucial to their success.

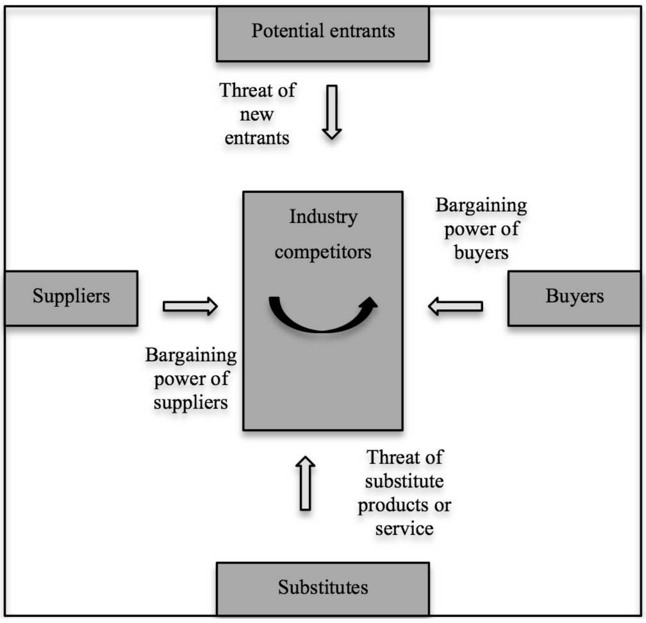

Figure 2: Porter's five forces
Source: Porter (1979)

3. The South African electric power industry

To be able to understand the environment in which the Western Cape solar service providers are operating, it is necessary to have background knowledge about the present electric and solar industry.

3.1 Energy context

The global energy industry created total revenues of $6.050 billion in 2009 (Datamonitor, 2009). Global electricity demand is predicted to increase by 35% until 2030. More specifically in the BRICS developing nations, it is expected to grow by 65% (International Energy Agency, 2013a). The performance of the industry is predicted to speed up, with an anticipated annual growth rate of 13.2% for the five-year period 2009-2014, which will drive the industry to a value of $11,250.4 billion by the end of 2014 (Datamonitor, 2009).

About 70 % of the total energy supply in South Africa derives from coal. Coal-fired power-stations supply 93% of electricity production. Given its coal-based energy economy, South Africa is one of the main emitters of greenhouse gases when compared to other developing countries (Pegels, 2010). In 2002, on the African continent, 90.6% of CO_2 was emitted by South Africa (United Nations, 2005). In 2005, South Africa was responsible for 1.1% of total global emission. Average per capita emission of 9 tonnes almost equalled to 10.7 tonnes in the EU (WRI, 2009). Since most forecasts indicate that coal will continue to be used in the near future, finding ways of using fossil fuels in a cleaner way is important during the conversion to different energy systems (Winkler, 2006). Possible technological options to produce cleaner electricity with coal are ultra-super-critical systems and an integrated gasification combined cycle (Liang, Wang, Zhou, Huang, Zhou & Cen, 2013).

Eskom is the state-owned electricity supplier, which is dominating the generation and capacity of energy. Furthermore, only about 70% of South African households are linked to the electricity supply grid, and overcoming energy poverty still remains a strategic development objective. In 2008 South Africa was unable to supply a vast number of households, and since then there have been a number of interventions to increase generation capacity (Edkins, Marquard, & Winkler, 2010a).

3.2 Solar market

Currently there are no subsidies for this technology, which makes it too expensive and not competitive enough to present sources of energy (Joburg, 2011). It takes more than seven years to amortise the initial investment in the panels by saving electricity. The fact that the majority of South African residents cannot plan ahead to stay for so many years in one place, makes this option highly unattractive (Addinall, 2011).

A study launched by the World Bank called the 'Renewable Energy Market Transformation' study, has identified the potential of Solar Water Heating (SWH) in the present and even more for the future (Conningarth Economists, 2004). The South African domestic water heating market is still dominated by electrical storage heaters. Less than 1% of homes in South Africa have solar water heaters, although conditions are favourable (DME, 2005). Another study conducted by the UNPD concludes that 30% – 40% of household consumption is caused by water heating, which includes a saving potential of up to 70% (Holm, 2005).

Every year around 480 000 electric water heaters are installed in South Africa (Edkins, Marquard, & Winkler, 2010b), in total there are just less than 8 million electrical heaters (Holm, Holm, Lane & Van Tonder, 1990; Geldenhuys, 1998).

3.3 Solar power

The on-going growing energy demand and the present power shortage in South Africa emphasize the need to utilize the rich renewable energy resources of the country. With an average of more than 320 sunny days a year, new approaches have to be conducted to increase the under-used application of solar power (Clean Project Analysis, 2004).

From an international perspective South Africa has several policy options available to promote renewable electricity, specifically solar power. Generally, there are two possible means of intervention for the government. One way is to regulate the quantity of renewable electricity; the second way is to fix prices through regulating tariffs (Winkler, 2005b).

The 'White Paper on the Energy Policy of the Republic of South Africa' from 1998 presented policies which could be seen as drivers of renewable energy deployment in South Africa. The document promoted the inclusion of the Independent Power Producers in South Africa's power generation (Pegels, 2010). Moreover, it emphasised the areas to be dealt with to create a suitable enabling environment for the promotion of renewable energy. The White Paper included financial and legal instruments, technology development, awareness creation, capacity construction and education (Edkins, Marquard, & Winkler, 2010a).

Under the Renewable Energy Independent Power Producer Procurement Programme REIPPPP, private power producers are invited to submit project proposals in a series of windows. The programme is strongly supported by the government (Department of Energy, 2012). In November 2012, the South African government signed ZAR47 billion worth of contracts with IPPs for 1.4 GW of renewable energy developed through the first window. Further contracts for 1.0 GW were signed in May 2013 in the second window. The government plans to bring 6.9 GW of renewable energy capacity online by 2020. The projects are all grid-connected and supply electricity to the national electricity grid of Eskom (Baker & McKenzie, 2013).

To actively encourage and promote the widespread implementation of solar water heating[2], Eskom has rolled out a large-scale solar water heating programme. The government has set a target for renewable energy to contribute 10 000 Giga watt hours (GWh) of final energy consumption by 2013. Solar water heating could contribute up to 23% towards this target. Solar power is one of the most effective renewable energy sources available. Water heating can be responsible for up to 50% of a household's electricity consumption (Eskom, 2011b).

At the moment, there are subsidies for solar thermal technology but no subsidies for photovoltaic solar technology from Eskom (Eskom Call Centre, 2012).

4. Problem statement

The South African solar industry is in its infancy, characterised by accelerated growth expectancy and fuelled by factors such as new governmental subsidies, the fluctuations of fossil fuel prices and the increasing focus on economical long-term sustainability (Renewable Energy World, 2009). The expected growth necessitates a focus on the market positioning of solar service providers in the Western Cape, with the aim of taking full advantage of the opportunities associated with this industry.

This paper aims to produce an adapted[3] model of Porter's value chain for the Western Cape solar service providers. In addition, key areas for development of the Western Cape solar service provider value chain are identified, and recommendations for improvement in the best interest of all stakeholders are presented.

5. Research methodology

The method used to clarify the research problem included a secondary research method, followed by a primary research process.

5.1 Secondary research

To conduct secondary research, data is used which is gathered and recorded by someone else prior to the current project (Zikmund & Babin, 2010). The mediums used were as follows: books, Internet, articles, masters and doctoral dissertations and case studies.

For this research, an extended literature review was undertaken to investigate the value chain model and Porter's Five Forces model, and both were applied to the South African context. The second part of this section entails definitions and concepts, which are important for the understanding of the study. The topic of general and solar energy in a global and domestic context is examined in the last section.

5.2 Primary research

Primary research is data collected or observed from first-hand experience (Business Dictionary, 2009). The different phases of the primary research of this research were as follows:

1. Preparation of a questionnaire according to objectives
2. Pilot study
3. Adjustment of the questionnaire according to pilot study and objectives
4. Main interviews (recording and notes)
5. Transcription of main interviews
6. Coding of data (content analysis)
7. Coding of data (frequency tables).

A questionnaire was set up according to the primary and secondary research objectives of the research. Every secondary research objective had its own question(s), which ensured that all information necessary to answer the objective was asked. The research included a pilot study at the beginning of the research. The purpose was to gain initial real-time information about solar service providers in the Western Cape (Hague & Jackson, 1995).

5.3 Target population

The target population of this research was solar service providers, who are active in the downstream solar value chain in the Western Cape. The service provider could be any type, from an online retailer to a physical location-based shop. Respondents were general managers or owners of solar service providers, the reason is their all-round knowledge of their company's business activities. The entire4 population of solar service providers in the Western Cape was targeted. Two Internet sites called 'Solar Suppliers' and 'the official Eskom site' list solar service providers in the Western Cape and represent the population for the main interviews. The main interviews included 18 managers/owners of different solar service providers in the Western Cape.

The population list of the present study was created through a variety of sources. Firstly, the official Eskom web page lists 55 service providers situated in the Western Cape. Secondly, an Internet site called 'Solar Suppliers' lists 33 solar service providers in the Western Cape, which are partly the same, but it also identifies different ones to those on the Eskom web page. The final population list included 77 different solar service providers, all of whom were contacted to take part in this study.

5.4 The questionnaire

The opening section provided the interviewee with an overview and information about the purpose of the study. The interviewer was introduced and the procedure explained (Willis, 2007). Moreover, the respondent was informed about the intended use of the data. The methods to keep information confidential were discussed and permission to tape record the interview was asked.

Section two of the interview was directed at the main themes identified in the literature review (Willis, 2007). The main themes were identified in the research objectives, namely the adaptation of Porter's value chain and the identification of key success areas. The guide allowed freedom to probe into answers and adapt to the situation in order to gain additional insight.

The closing section was about future perspectives and opportunities. The main issues discussed during the interview were summarised and the interviewees were motivated to add more of their relevant knowledge (Willis, 2007). Furthermore, future action was mentioned, by asking each interviewee for availability of additional telephonic questions. Lastly, the respondent was thanked for his or her time.

To ensure reliable and valid data, every respondent was presented with the same procedure (ASCD, 2010).

5.5 Data analysis

The qualitative data gathered (pilot and main interviews), with semi-structured interviews, was in the form of open-ended responses, which were transcribed. The questions were in exploratory form. The transcribed interviews were coded using a content analysis approach (Colorado State University, 2010).

After the data was coded and common themes were recognised, frequency tables were created to analyse the rate of occurrence of each identified theme (Hague & Jackson, 1995). A frequency rate of 60% and higher was categorised as a commonality or similarity. A frequency rate of less than 60% was classified as a trend or difference.

The interpretation of identified themes and categories confirmed trends, differences, commonalities and similarities of activities in the solar service provider value chain. The interpretation of primary and secondary data helped in the generation of an adjusted value chain model. The value chain was adjusted only with commonalities of more than or equal to a frequency of 60%. The data identified key areas for the development of the Western Cape solar service provider value chain, which involved all themes and categories with more than, and less than, a 60% frequency.

6. Summary of main findings

This section presents the most significant findings of this research. To create more understanding , the sections start with the most basic findings.

6.1 The stakeholders

To create recommendations that would improve the relationships with the most important stakeholders, respondents were asked to select the main stakeholders to their business. Those most frequently selected were suppliers (89%), employees (83%) and customers (78%). The business relationship with all three main stakeholders was based on legal contracts. The biggest concern expressed by 67% of the respondents was the relationship with customers. This stakeholder group still had to be educated about the benefits of solar energy, without being concerned about the initial investment.

6.2 The solar service provider value chain

Part of the primary objective of this research was to adapt Porter's value chain model to the business activities of solar service providers in the Western Cape. The adapted solar service provider value chain model is presented in Figure 3. Most service providers (56%) pursued a best-cost provider strategy, as customers demanded good performing products without an enormous initial investment. The secondary activities were on top, and are as follows:

- *The human resource management* function was mentioned as the most important one, as it was responsible for good service, which was a strong differentiation point. To employ new staff members, education (83%) and personal reference (72%) were the foremost important criteria. To keep staff members motivated in 55% of the cases, personal recognition was used, followed by 38% for incentives.
- *The technology* represented the products, which were sourced from suppliers. Good technological products were a basic requirement to become a sustainable contender in the market.
- *Order procurement* was essential for the business, which meant they had to perform well in order to enter the market. It organised the product buying process at the optimal possible cost at the correct amount and quality.

The primary activities in Figure 3 were at the bottom, and formed the core business process of a solar service provider. The primary activities identified were as follows:

- *Marketing* was the first step as it was necessary to make the customer aware of the product. Residential areas were targeted from nearly all (89%) of the service providers, followed by businesses (45%). The most common marketing tools used at the time were websites, word of mouth and paper advertisement. Satisfied customers generated word of mouth.
- *Solar service provider handles customer contact* after he gained awareness through the marketing. The contact channels were e-mail in 89% of the cases, followed by phone and personal visits with 72% and 50%.
- *Site visits* were done by solar service provider staff members to evaluate the location at the customer's place, and to find the most suitable product solution.
- *The quotation* was prepared and sent to the customer after the target location was evaluated and the appropriate solution was found. The best sold products were geysers with 89% and solar water heaters with 83%. The most important product preferences for all products were price and quality.
- *The order, manufacturing and inventory* step made sure all product parts for the demanded installation were ready. The majority of service providers sourced their products from South African suppliers (55%), followed by European (30%) and Chinese (15%). The European products had the best overall measured rating, with the only disadvantage of high prices. South African products were in second place, with lower ratings than the European products and prices, which were also rated as too high. Chinese products got the lowest overall rating, but the prices offered were lower.

The service providers either received their products through agents or at collecting centres. It depended on the product and whether stock was kept, for the most popular products 67% of the service providers kept stock. On an average the stock lasted for 7 weeks.

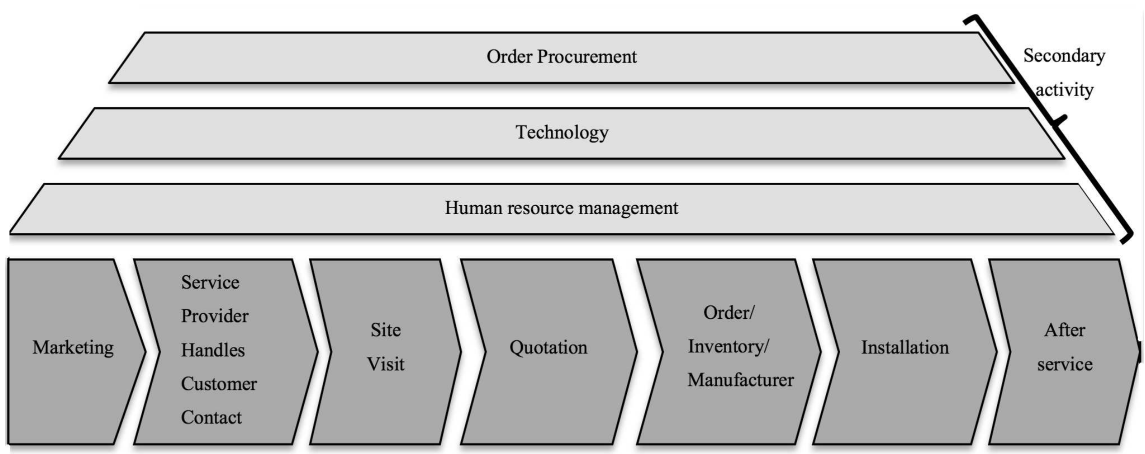

Figure 3: The solar service provider value chain

Product training and weekly check-up calls were services that were provided by 84% of the suppliers. A two-way communication approach between supplier and service provider was performed by 75% of the existing relationships. The frequency of communication depended on the service provider, which made contact at least once a week. The most common communication channels were e-mail (89%), phone (78%) and face to face communication (50%).

- *The installation* takes place when the products demanded by the customers are put into place at the desired location. Within the first week 89% of the orders were installed. In 78% of the cases, the customer had to settle the outstanding amount in the first week after the installation was finished.
- *The after-service* took place after the installation and payments were made. The purpose was to assure that the product performed as promised. In 55% of the cases, a check-up call was conducted from the service provider, and 33% did not have any after-service.

The majority of managers (67%) were aware of the value chain concept and how to apply it to their business. It is interesting to mention that only managers who approached a best-cost provider and differentiation strategy were conscious of the concept. Only 37% of employees were aware of the concept. Repeatedly, only employees of service providers with best-cost provider and differentiation strategies used the concept. The awareness of the supporting activities was high, with 89%.

6.3 The value chain key success factors

These factors are part or are one of the activities of the adapted value chain in Figure 3. For solar service providers to be sustainable and competitively superior, it is important to perform exceptionally in these activities.

The foremost important value chain activity was service, which was mentioned by 94% of the respondents. Service forms part of virtually every value chain activity. However, the most important service activities were the site visit and the installation. The employee is in face to face contact with the customer and has to ensure that the products are set up properly. Moreover, good service has a strong influence on positive word of mouth.

The second most important activity was marketing, which was chosen by 39% of the respondents. Based on the fact that the industry is still in its infant stage, customers have to be made aware and to be educated about the product offers of solar service providers. The products last more than 20 years, which makes it important to gain new customers. Positive word of mouth is consequently a good way to gain new buyers, and is crucial for sustainability.

6.4 The five forces and solar service providers

The force of new entrants was mentioned the most and was selected by 50% of the respondents. Reason for this was the strong growing market, which created space for new market entry. Most new entrants offered cheap products from China, which harmed the market reputation as the performance was low in comparison to European and South African quality. Moreover, no service provider could establish himself as a clear market leader yet.

The forces of substitutes and buyers were selected each with 28%. The major substitute for solar energy is the still relatively cheap common electricity delivered by Eskom. This substitute is expected to become weaker as the electricity price is going to increase in future. The power of buyers is considerably high as there are more service providers entering the market, which gives a greater variety to choose from.

Most of the respondents mentioned installations as their core competency, followed by technology and reputation. In addition, respondents were asked to identify their strongest competitor(s). The strongest contender in the Western Cape market was SolarTech, followed by SolarMax.

6.5 Relevant cross-sectional findings

Considerable findings could be made, based on the strategy the solar service provider is pursuing. The best-cost provider strategy was the most successful one with an annual sales increase of 23%, followed by a differentiation strategy with 7%. All other strategies had decreasing sales numbers.

Best-cost providers sourced their products from local suppliers, as they had a good quality/price ratio. Moreover, the delivery time was one week in comparison to overseas products of two weeks. Service providers with differentiation strategies sourced from European suppliers as the quality was superior, but with the disadvantage of a high price.

The target market with the highest sales increases with 37% was public institutions and hotels. The second strongest was residential areas with a 2.8% increase, which was also the most popular one.

7. The advanced solar service provider business structure

The advanced solar service provider business structure, including the recommendations, is illustrated in Figure 4. The recommendations are underlined and are discussed in more depth in this section.

The best-cost provider strategy was selected as the most appropriate one for solar service providers. The first reason is that many potential customers fail to purchase the solar product as the initial investment is too high. The strategy offers a lower initial investment, which makes it affordable for more customers. Secondly, the quality has to be high, as the solar technology is still in the beginning of its life cycle. For instance, a low cost quality solar water heating system does not efficiently heat the water, which causes dissatisfaction for the customer.

The solar service provider can specialize in certain types of customers. One target market yields more potential are businesses. The type of product provides another opportunity to specialize in. It would save time and costs to specialize in solar water heating systems, as the popularity is increasing.

The flagship products are geysers and solar water heating panels. The reason is that the technology is relatively advanced, which means it is durable, effective and reliable. Moreover, Eskom is providing subsidies for each SABS-approved system sold.

7.1 Marketing

Marketing is crucial for solar service providers, as the products offered in the market are very similar. Customer retention in the market is very low, as once a customer has bought a solar system, which lasts for at least 15 years, he is highly unlikely to come back for another one. Moreover, customers have to be made aware and educated about the benefits. The following section explains the customised marketing approach:

- *Provide incentives to customers who bring a new customer.* The main marketing aim should be to attract new customers. The incentive could be free service of the installed products for X amount of years, which also keeps the customer reminded of the service provider. Another approach could be to refund a part of the customer's bill. This approach would assist in increasing the most powerful marketing tool, word of mouth. Moreover, as there is no major market leader and service providers are of small size, the capital available for marketing is not enough for big campaigns. In addition, this tool would be directed to the local target market, and no extra effort has to be made.
- *Create a marketing pool to generate more power.* The campaign will have a wider reach to educate and increase awareness of the products and their benefits. Nevertheless, this is a long-term goal, as it requires trust and planning between the partners. The partnership could target a region, like the Western Cape.
- *Promote the products at functions.* It is important that the target consumers are present and are reached.

All marketing recommendations take the present business structure of the majority of solar service providers into consideration. Firstly, the business is small, which means limited funds for marketing, and target customers are in a small area. Secondly, most competitive pressure is created by new entrants who make it important to be established in the local market. Consequently, to be successful, the small service provider should create a reliable and professional reputation in his local market.

7.2 The service

In Figure 4, the service parts are underlined, including the mission (customer satisfaction) and after-sales service. The following recommendations indicate how to improve these activities:

- *The mission statement aims to create customer satisfaction.* Solar service providers formulated well defined mission statements even though it was very vague and broad, and still lacking in implementation and execution. The performance evaluation of all suppliers and their product is good to very good. Consequently, the service the business is providing is the crucial point to satisfy the customer and to be different from competitors.

  The installing team is therefore the key to fully satisfying the customer. The respondents knew that installing was the key, but they could not tell what they could do to improve their performance. To gain positive customer feedback, the installer also needs to be trained on interaction with the customer. To ensure excellent service, the service provider should train the installer team in all service dimensions:
- Reliability is the ability of an installer to perform the promised service dependably and accurately. This means that employees must be trained well on the products and how to install them.
- Responsiveness is the willingness to help and provide prompt service. For the installers, this means that they have to be in time for their appointments with the customer. Moreover, if there are any problems with the product, the installer has to be able to come the same day to fix it.
- Assurance is the employees' knowledge and courtesy and their ability to inspire trust and confidence.
- Empathy is to care and to give individualised attention to customers. The installers should be trained in communicating with customers.
- Tangibility is the appearance of physical facilities, equipment, personnel, and written materials. The equipment, including the car, should be clean and organised.
- *After-sales-service* is often underestimated in contributing to overall customer satisfaction. At the start, a check-up call should be conducted to ask if everything is working. To improve the service enormously, service providers should conduct a last visit to check the functionality of all products.

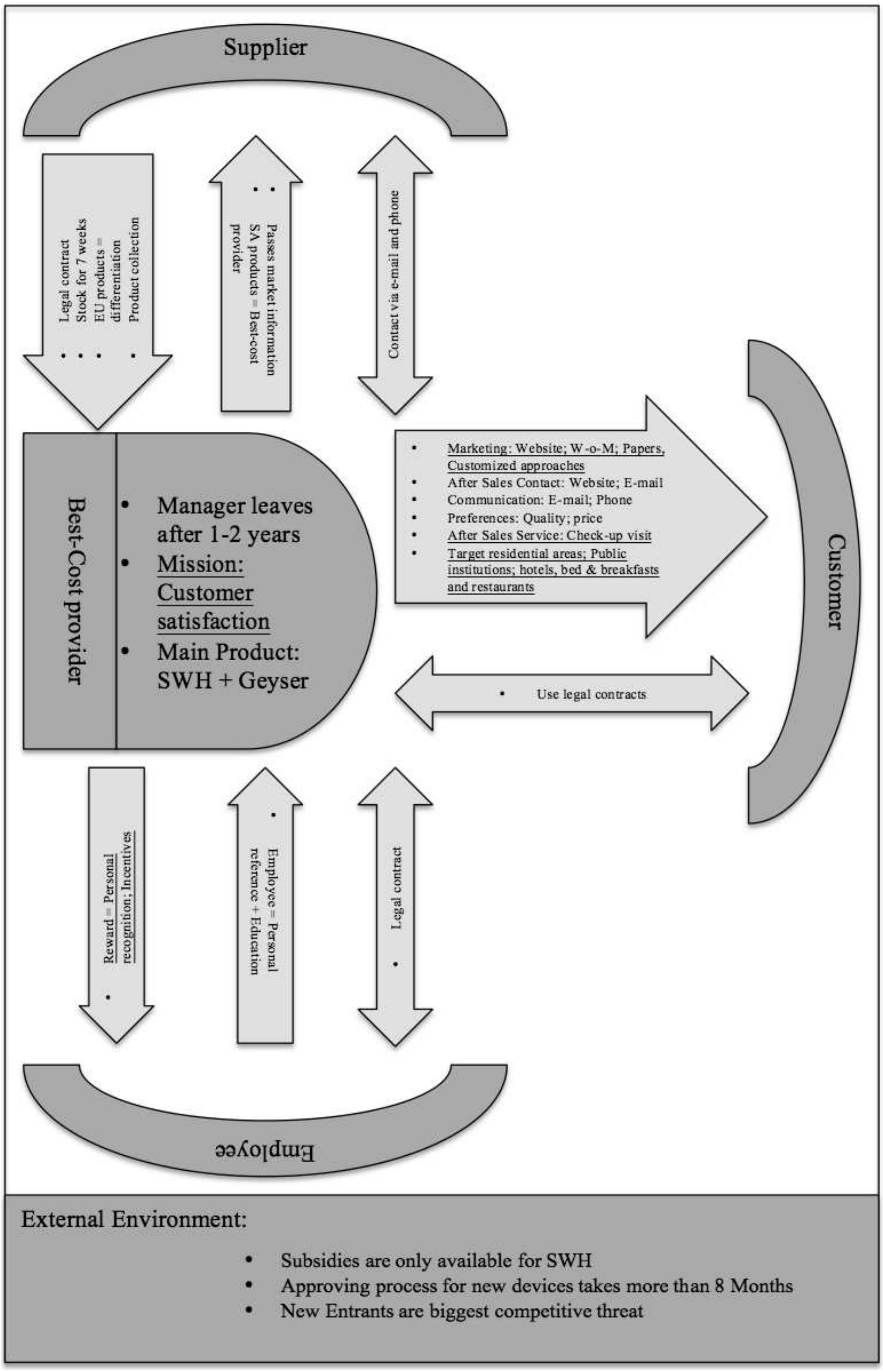

Figure 4: Advanced solar service provider business structure

7.3 Employee motivation

The employees are the capital of a solar service provider business. This section provides recommendations of how to improve the motivation of employees. The following are two possible tools for further motivation:

- *An incentive* is extra salary paid to the employee for each successful installation. For instance, the installer team can receive for each successful job an X amount of money. This amount is distributed after the final check-up visit/ call when the customer has expressed his satisfaction.
- *Bonuses* are used on a monthly basis and are added to the basic salary. Bonuses are generated and distributed to employees when monthly predicted profits are exceeded.

As employees, especially installers, should only be focused on their present installation, it is advisable to use incentives. The advantage is that the installer knows that for each job he does well, he gets extra money. Bonuses can also be used but are more suitable for employees who are not directly linked to the main service, the installation.

8. Conclusion

The main outcome of this study is the adapted model of Porters' value chain to solar service providers in the Western Cape. The literature review of this research has shown that it is crucial for the sustainable future of South Africa to increasingly make use of renewable sources of energy. As mentioned before, the high sun radiation level presents optimal conditions for the usage of solar technology in South Africa. In addition, the present development of the rising electricity costs makes it progressively more economical to invest in renewable sources of energy.

The supplier side of the industry is developed, as can be seen in countries such as Germany, where the technology is well accepted. The downstream part of the South African solar industry is in its infant stage, which creates space and the need to improve. To increase the usage of solar energy in South Africa, this research aimed to improve the performance of solar service providers.

The recommendations of this paper show that solar service providers need to improve their service and marketing performance. Marketing is important as customers still have to be educated about the benefits of solar products. High qualitative service is crucial, as solar panels cannot perform at their maximum and capture all the possible sun radiation if installed poorly.

Notes

1. Atmospheric gases that contribute to the greenhouse (global warming) effect by absorbing infrared radiation produced by solar warming of the Earth's surface. Most common gases are carbon dioxide, methane and nitrous oxide (Science dictionary, 2010).
2. There are two broad categories of solar power known. The first category is called 'solar water heating', where the sun radiation is used to heat water up. The second category uses the sun radiation to produce electricity, which is called 'photovoltaic solar power'.
3. The customisation of Porter's generic value chain model to the business activities of Western Cape solar service provider.
4. Most care was taken that the list of solar service providers was up-to-date at the time the research was undertaken.

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Received 14 November 2012; revised 20 May 2014

Performance of a compression ignition engine operated with sunflower ethyl ester under different engine loads

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Abstract

This study investigated the performance of a compression ignition engine operating with sunflower ethyl ester. A thermodynamic analysis, including energy and exergy analysis at different engine loads (20%, 40%, 60%, 80%, 100%), was conducted. The study calculated the first and second law efficiency, effective work, heat exergy losses and exergy destruction values at 10 different engine speeds for 5 loads. Maximum work, maximum thermal efficiency, maximum exergy efficiency and maximum volumetric efficiency are determined to be 6.45 kW, 0.26, 0.24 and 0.71 respectively. Finally, optimum operating conditions are discussed and it was determined that the engine should be operated at a lower engine speed for partial loads.

Keywords: energy analysis, exergy analysis, exergy destruction, biodiesel, ethyl ester

1. Introduction

Diesel engines are widely used in a variety of vehicles due to their high fuel efficiency and low cost compared to other fuel engines. The resources of petroleum as fuel are dwindling day by day and the increasing demand for fuels, as well as increasingly stringent regulations, pose a challenge to science and technology. The commercialization of bioenergy has provided an effective way to fight the problem of petroleum scarcity and petroleum consumption's influence on the environment. All of these problems have motivated the scientific society to seek new, alternate energy sources that have lessened the effects of global warming and pollution. At this point, the scarcity of known petroleum reserves and increasing environmental consciousness has made renewable energy sources more attractive (Misra and Murthy, 2011; Moron and Villareyes, 2007). As a renewable, sustainable and alternative fuel for compression ignition engines, biodiesel instead of diesel has been increasingly used to study its effects on engine performance and emissions in the last 10 years. The advantages of using biodiesel as diesel fuel are minimal sulphur and aromatic content, and the higher flash point, lubricity and cetane number. It helps to reduce carbon dioxide emissions in the atmosphere; it is renewable in nature and safer to handle; it has no aromatic compounds, practically no sulphur content, and oxygen atoms in the molecules of the fuel may reduce the emissions of carbon monoxide (CO), total hydrocarbon (THC) and particulate matter (PM) (Scholl and Sorenson, 1993; Lapuerta *et al.,* 2005; Lapuaerta, Armas and Ballesteros, 2002; Zang and Van Gerpen, 1996).

The combustion performance of the ethyl ester of used palm oil relative to baseline diesel fuel in a water-cooled furnace was investigated. The combustion efficiency was tested over a wide range of air/fuel ratios, ranging from very lean to very rich (10:1–20:1). The findings showed that at a lower energy rate, biodiesel burned more efficiently with higher combustion efficiency (66%) compared to the diesel fuel (56%). At higher energy inputs, the biodiesel combustion performance deteriorated, because of its high viscosity, density and low volatility (Tashtoush, Al-Widyan and Al- Shyoukh, 2003). Rakopoulos *et al.,* (2011) conducted a study to evaluate the use of sunflower, cottonseed, corn and olive straight vegetable oils of Greek origin, in blends with diesel fuel at proportions of 10% and 20%. The study reported that the specific fuel consumption for all vegetable oil blends is a little higher than the corresponding one for the diesel fuel case. The engine brake thermal efficiency with all the vegetable oil blends was practically the same as that of the neat diesel fuel case.

In recent years, the exergy analysis method has been widely used in the design, simulation and performance assessment of various thermal systems. This analysis is based on the second law of thermodynamics. Exergy is defined as the maximum theoretical useful work obtained as a system interacts with the equilibrium state. Exergy is generally not conserved as energy but destroyed in the system. It is possible to determine the optimum speed of an auto cycle engine using combined energy and exergy analysis. Energy and exergy efficiencies are calculated for different engine speeds and compared. Determination of the optimum engine speed should not be based on energy analysis alone (Kopaç and Kokturk, 2005). Exergy destruction is a measure of irreversibility that is the source of performance loss.

Investigated is the effect of varying dead state temperatures on the exergy efficiency of a high-oleic methyl ester (HOME) fueled internal combustion engine (ICE). This engine is a 4.5L, four stroke, four-cylinder, turbocharged, 66.5 kW maximum power capacity John Deere 4045T diesel engine run with HOME, which is genetically modified with a high-oleic soybean oil methyl ester. The results obtained are discussed from the exergetic point of view. It was found that exergetic efficiency increased as the dead state temperature decreased. As a result, exergy efficiency values ranged from 29.78% to 34.93% based on dead state temperatures between 5 °C and 30 °C (Caliskan, Tat and Hepbasli, 2009). There has also been presented a comparative second law analysis of internal combustion engine operation for methane, methanol and dodecane fuels (Rakopoulos and Kyritsis, 2001). Analyzed is a diesel cycle considering combustion and heat transfer effect on performance. The effects of the compression ratio and cut-off ratio on the heat transfer were analyzed. Exhaust temperature and work output increased (Parlak, 2005). Energy and exergy analyses were performed in a four-stroke turbocharged diesel engine fuelled with No. 2 diesel and two different biodiesel fuels. Exergy efficiencies are calculated between 37.46 % and 38.48 %, with no statistically significant difference. Exergy destruction of the engine is between 59.03 kW and 61.76 kW for three fuels (Caliskan *et al.*, 2010).

Evaluated is the performance of an internal combustion engine at the steady-state condition through energy and exergy analysis by using experimental test results. The energy efficiency has a maximum point at the speed of 2500 rpm. The exergy analysis reveals that the engine's optimum speed is 300 rpm, as the exergy efficiency has a maximum magnitude at this speed (Ameri *et al.*, 2010). The use of biodiesel and their blends results in a very similar exergetic performance with No. 2 diesel fuel in terms of fuel exergy input, exergetic efficiency, exergy destruction and exergy losses. Exergy losses due to the exhaust gas and heat transfer are other contributors in decreasing order (Canakci and Hosoz, 2006). Using exergy as a measure of quality, the petroleum diesel fuel is of greater quality than biodiesel because of the net calorific value of diesel that of biodiesel (Sekmen and Yilbasi, 2011).

The energy demands of the world increase day by day. That's why using and exploring different energy resources like biodiesels have gained importance. Sunflower ethyl ester is assumed to be a renewable energy source, and it can be used in internal combustion engines. In this study, a compression ignition engine operating with sunflower ethyl ester was investigated for different engine loads. This is because engines usually operate at less than full load. Energy and exergy analyses were performed and optimum operating conditions were determined.

2. Materials and methods

Sunflower ethyl ester was the test fuel. The physical properties of the fuels tested are presented in Table 1. The tests were conducted on a single cylinder, four stroke, naturally aspirated, air cooled diesel engine coupled with an electrical dynamometer. A schematic diagram of the systems can be seen in Figure 1. The detailed technical specifications of the engine are given in Table 2. The test fuels are 100 % ethyl ester; the biodiesel molar ratio of alcohol to oil used was 5:1, whereas the catalyst amount was 1% of the oil's weight.

Table 1: Physical properties of the sunflower ethyl ester (SFEE)

Specification	*Test method*	*Units*	*SFEE*
Viscosity (40 °C)	EN ISO 3104	mm^2/s	5.2
Density	EN ISO 3675	kg/m^3	887
Flash point	EN ISO 3679	°C	128
Cetane index	EN ISO 5165	Calc.	49
LHV	DIN 51900	kJ/kg	30436
Carbon mass		%	77
Hydrogen mass		%	11.7
Oxygen mass		%	11.2

The air and fuel flow rates entering the engine were measured using a laminar flow element and a digital scale, respectively. Temperature measurements at different locations of the experimental system were conducted using thermocouples. Energetic and exergetic values were calculated by a 300 1/min increase in fixed cycle variable speed experiments.

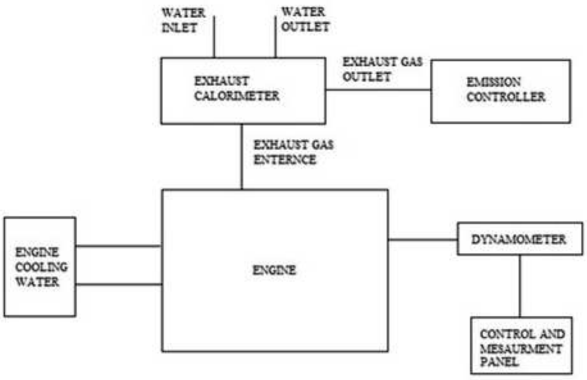

Figure 1: Schematic diagram of engine test unit

Table 2: Technical properties of the engine used in the experiment

Model	*Ricardo Hydra*
Cylinder	1
Cylinder Diameter	80.26 mm
Stroke	88.9 mm
Compression Ratio	19.8/1
Valve Setting	OHC, two valve
Max. rpm	4500 1/min
Injector	4x0.21 x 155°

3. Thermodynamic analysis

Energy and exergy analyses were conducted under steady-state conditions for the control volume. An energy analysis for the control volume can be written by means of the first law of thermodynamics (Moran and Shapiro, 1995; Cengel and Boles, 2008).

$$\sum_{in} \dot{E}_{in} - \sum_{out} \dot{E}_{out} + \sum \dot{Q} - \dot{W} = 0 \quad (1)$$

Where in and out represent input and output states respectively. $\dot{W}$ and $\dot{Q}$ denote work rate and heat rate. Energy input to the system is the chemical energy of fuel, which is calculated as the following (Kopaç and Kokturk, 2005; Caliskan et al., 2010 and Ameri *et al.*, 2010):

$$\dot{Q}_H = \dot{m}_f LHV \quad (2)$$

Where m is the mass flow ratio and LHV is the lower heating value of the fuel. Effective work of the engine can be calculated as (Kopaç and Kokturk, 2005; Caliskan et al., 2010 and Ameri *et al.*, 2010):

$$\dot{W}_E = \frac{\pi n}{30}\tau \quad (3)$$

Here, n is the engine speed and τ is the torque. Heat loss from the exhaust is (Caliskan *et al.*, 2010):

$$\dot{Q}_{EX} = \frac{\dot{m}_w c_{p,w}\left(T_{w,2} - T_{w,1}\right)}{\left(T_{e,2} - T_{e,1}\right)}\left(T_{e,1} - T_0\right) \quad (4)$$

Heat loss with other processes (radiation, cooling water and lubrication oil) is calculated as follows:

$$\dot{Q}_O = \dot{Q}_H - \dot{W}_E - \dot{Q}_{EX} \quad (5)$$

The energy efficiency of the system can be described as the ratio of the work output of the engine to the fuel energy (Moran and Shapiro, 1995; Cengel and Boles, 2008):

$$\eta = \frac{\dot{W}_E}{\dot{Q}_H} \quad (6)$$

In exergy analysis, the dead state was assumed as 298.15 K and 100 kPa. From the second law of thermodynamics, entropy and exergy analyses for the control volume can be described as the following, respectively (Moran and Shapiro, 1995; Cengel and Boles, 2008):

$$\sum \frac{\dot{Q}_k}{T_k} + \sum_{in} \dot{S}_i - \sum_{out} \dot{S}_{out} + \dot{S}_{gen} = 0 \quad (7)$$

$$\sum \left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k + \dot{E}x_W + \sum_{in} \dot{E}x_i - \sum_{out} \dot{E}x_{out} - \dot{E}x_D = 0 \quad (8)$$

Where $\dot{S}_{gen}$ and $\dot{E}x_D$ represent the entropy and the exergy rate respectively. The exergy of a substance is (Moran and Shapiro, 1995; Cengel and Boles, 2008):

$$\dot{E}x = Ex_p + Ex_{ch} \quad (9)$$

Exergy transferred with heat can be described as (Moran and Shapiro, 1995; Cengel and Boles, 2008):

$$\dot{E}x_Q = \dot{Q}\left(1 - \frac{T_o}{T_k}\right) \quad (10)$$

where T_o is the environment temperature and T_k is the high temperature source. Exergy transferred with work is equal to work done by the engine (Moran and Shapiro, 1995; Cengel and Boles, 2008):

$$\dot{E}x_w = \dot{W}_E \quad (11)$$

The exergy input of the system is equal to the chemical exergy of the fuel (Kopaç and Kokturk, 2005; Caliskan *et al.*, 2010 and Ameri *et al.*, 2010):

$$\dot{E}x_H = \dot{m}_f \alpha_f LHV \quad (12)$$

Where α_f is the chemical exergy factor, and it can be calculated as (Moran and Shapiro, 1995):

$$\alpha_f = \left[1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{s}{c}\left(1 - 2.0628\frac{h}{c}\right)\right] LHV \quad (13)$$

where o,c,h and s represent the mol weight of the elements. The physical exergy of any system is (Moran and Shapiro, 1995; Cengel and Boles, 2008):

$$\dot{E}x_P = \dot{m}\left(h - h_o\right) - T_o\left(s - s_o\right) \quad (14)$$

Where h is the specific enthalpy and is the specific entropy. The chemical exergy of a gas mixture can be calculated as (Kopaç and Kokturk, 2005; Ameri *et al.*, 2010):

$$\dot{E}x_c = RT_o \sum_{i=1}^{j} y_i \ln \frac{y_i}{y_i^e} \quad (15)$$

where R is ideal gas constant and y is mol ratio. Exergy is the rate of effective work to fuel exergy (Moran and Shapiro, 1995; Cengel and Boles, 2008):

$$\varphi = \frac{\dot{W}_E}{\dot{E}x_H} \quad (16)$$

4. Results

Experiments were conducted at different engine loads and at different engine speeds for a compression ignition engine operating with sunflower ethyl ester. Results are shown in Figure 2-26. After investigating these figures, results can be presented as follows.

4.1 Energy

Energy related figures can be seen in Figures 5, 10, 15, 20 and 25. Other heat losses include radiation and cooling water losses. Other heat releases reached their maximum values between 3 300 rpm and 4 200 rpm for all engine loads. In addition, it can be seen that other heat losses generally increase with engine speed. Exhaust heat loss is greater at low engine speeds (1500-2400 rpm) for 20-80% engine loads, however, exhaust loss is nearly the same at all engine speeds for 100% engine loads. For all engine loads, except 100%, work efficiency is greater at low engine speeds (1500-2400 rpm) and it obtains the minimum value at 3000 rpm, however, with a 100% engine load it gets its maximum at 2400 rpm and its minimum is at 4200 rpm.

4.2. Exergy

Exergy related values are shown in Figures 6, 11, 16, 21 and 26. Exergy destruction is the highest value according to exergy analysis. The reasons for exergy destruction in the engine are friction, heat losses, and most importantly, the combustion process which, it can be seen, is getting bigger.

Investigating exergy destructions, it values, generally, at the high engine speeds for 20-80% engine loads. However, with 100% engine loads, all exergy destruction rates are nearly the same for all engine speeds. Exergy destruction can be decreased by increasing the air-mass ratio (Rakopoulos and Kyritsis, 2001).

In addition, exhaust heat loss exergy doesn't tend to follow any pattern for engine speeds at the partial engine loads, and heat release exergy reaches its minimum at 2700-3000 rpm, but at the full load, it is more balanced and has similar values. When results are investigated, it can be seen that maximum work (6.45 kW) is obtained at 3900 rpm for 100 % engine load; similarly minimum work is obtained (1.27 kW) at 300 rpm for 20 % load.

4.3 Effective work and torque

For 20 and 40% engine loads, maximum work is obtained at engine speeds (2100 and 2400 rpm), but, with 60, 80 and 100% engine loads work reaches it maximum at 3600 and 3900 rpm values. Work shows unbalanced changes at the partial loads, while it is balanced at full load. This is because the combustion process is more effective with the full load. The ratio of effective work to energy and exergy analysis decreases with engine speed.

Similar to effective work, torque values show unbalanced changes at partial loads, and it is balanced at 100% engine loads. With all engine loads, maximum torque values are obtained at a low engine speed (1500-2400 rpm) and generally, torque value is lower at high engine speeds. It reaches its minimum at 20% load and 3000 rpm (3.799 Nm) and its maximum at 100% load and 2400 rpm (20.303 Nm).

4.4 First law (energy or thermal), second law (exergy) and volumetric efficiencies

Results for energy efficiency show that maximum efficiency is obtained at 1500 rpm with 20% load, while minimum efficiency (0.064) is at 4200rpm with 20% load again.

Maximum exergy efficiency (0.24), as with energy efficiency, is reached at 1500 rpm for 20% load and minimum exergy efficiency (0.07) at 4200 rpm for 100%. Energy and exergy efficiencies are greater for low engine speeds than high engine

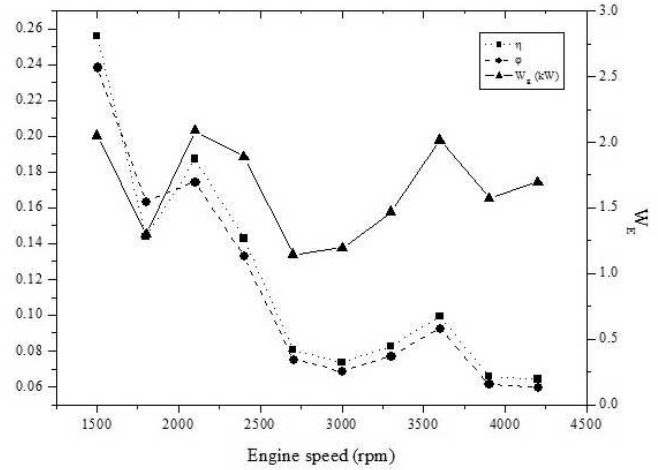

Figure 2: Effective work, energy and exergy efficiencies of the engine operating with sunflower ethyl ester at 20% load

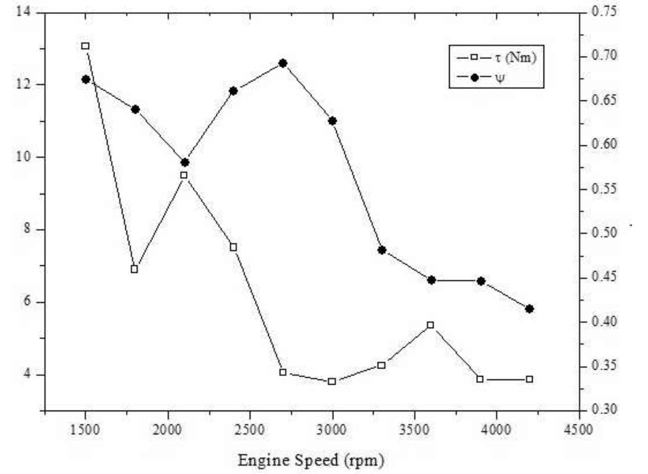

Figure 3: Torque and volumetric efficiency with sunflower ethyl ester at 20% load

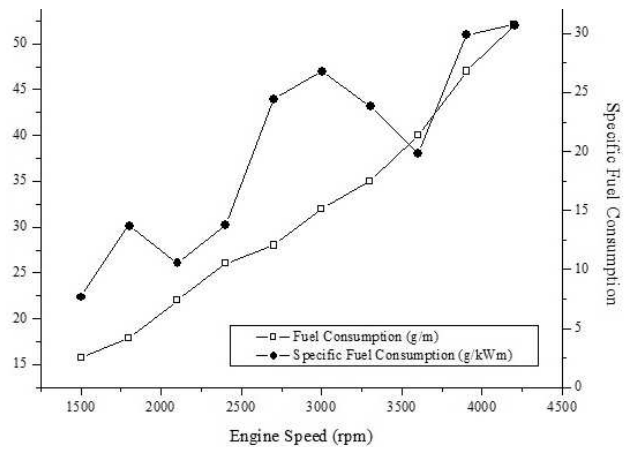

Figure 4: Fuel consumption and specific fuel consumption with sunflower ethyl ester at 20% load

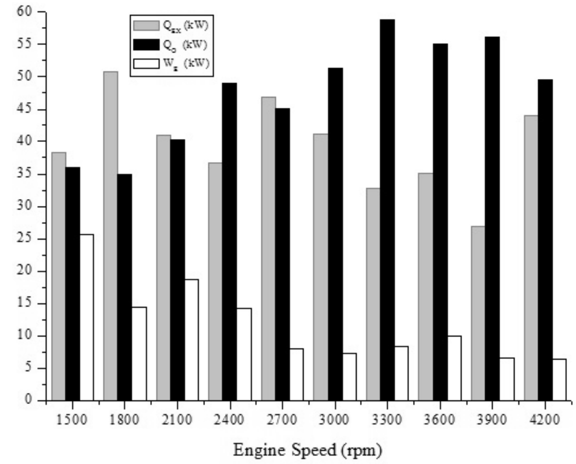

Figure 5: Breakdown of the energy at 20% load

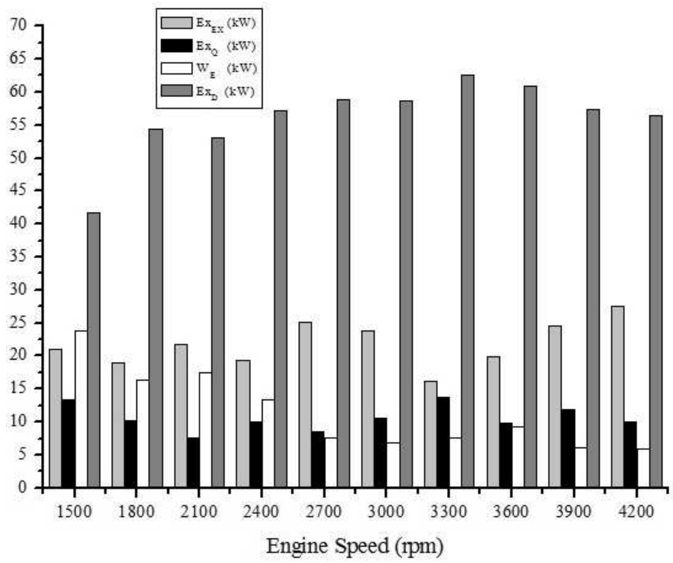

Figure 6: Breakdown of the exergy at 20% load

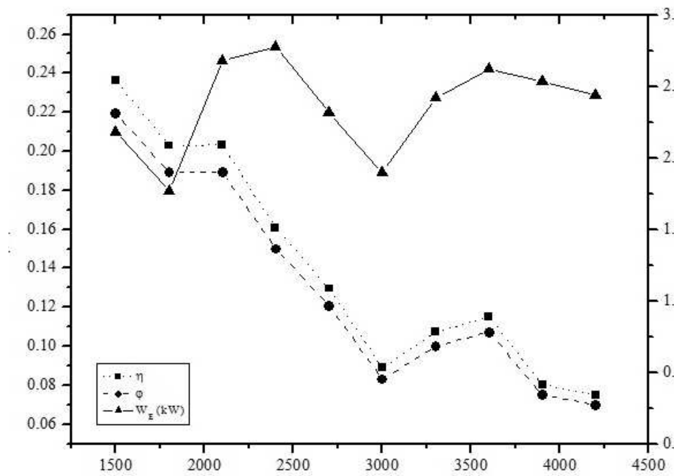

Figure 7: Effective work, energy and exergy efficiencies of the engine operating with sunflower ethyl ester at 40% load

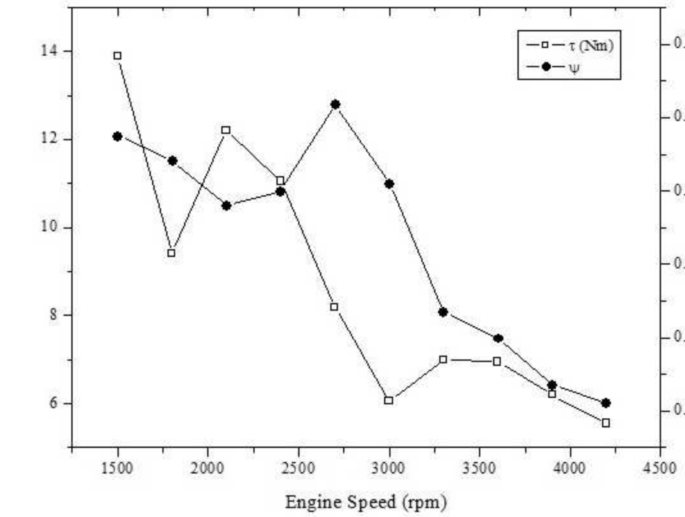

Figure 8: Torque and volumetric efficiency with sunflower ethyl ester at 40% load
consumption with sunflower ethyl ester at 40% load

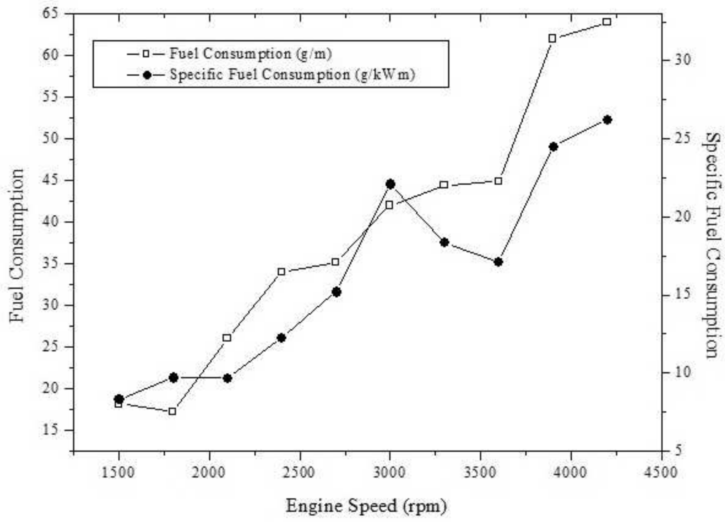

Figure 9: Fuel consumption and specific fuel

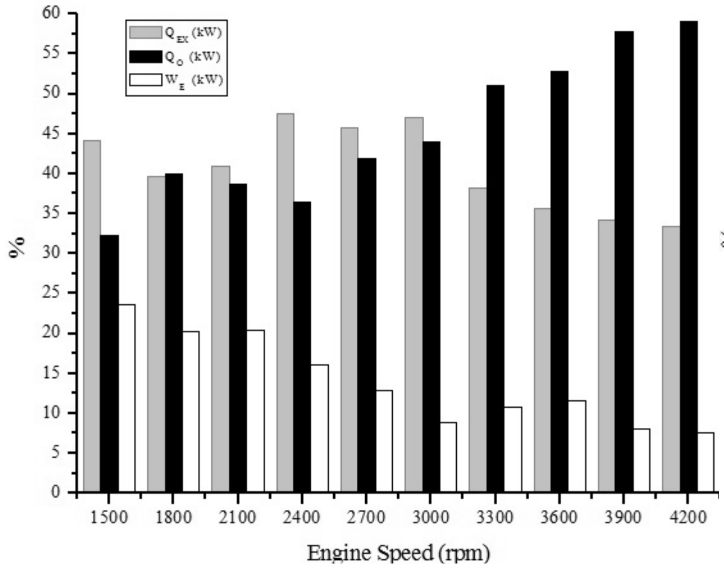

Figure 10: Breakdown of the energy at 40% load

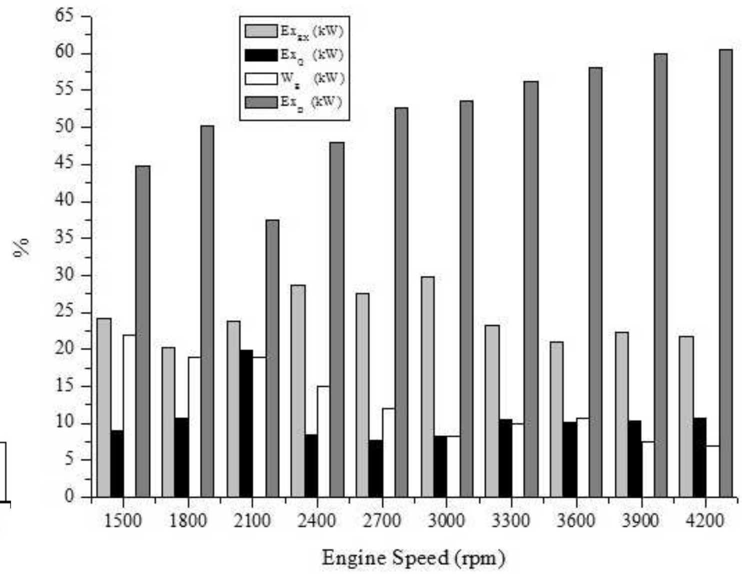

Figure 11: Breakdown of the exergy at 40% load

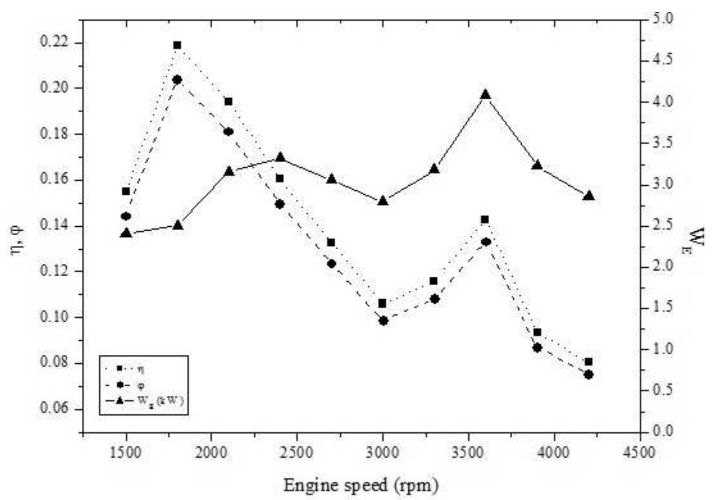

Figure 12: Effective work, energy and exergy efficiencies of the engine operating with sunflower ethyl ester at 60% load

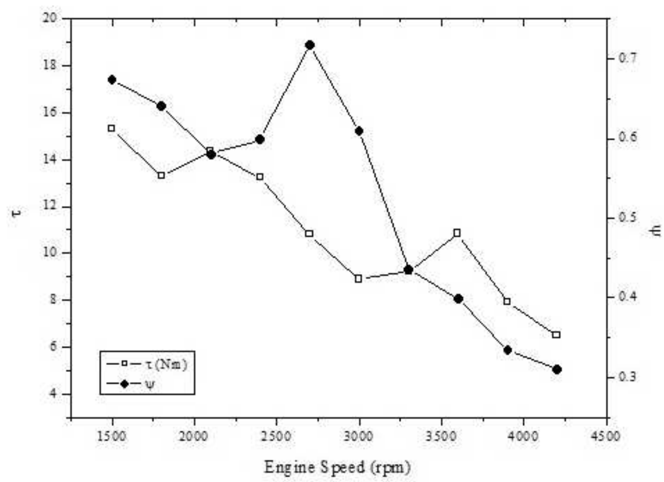

Figure 13: Torque and volumetric efficiency with sunflower ethyl ester at 60% load

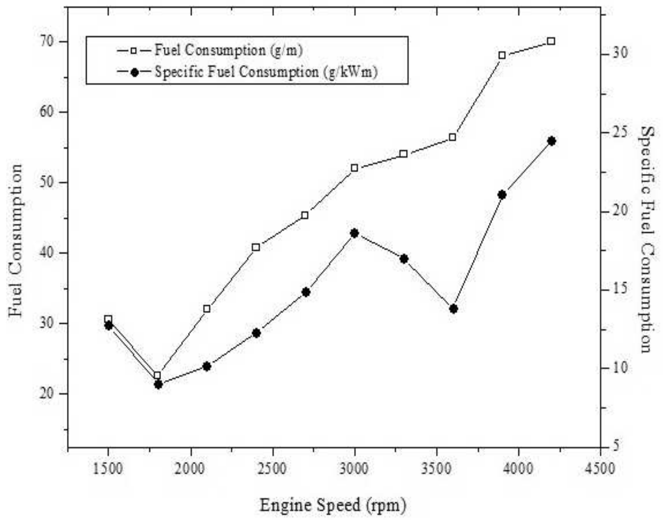

Figure 14: Fuel consumption and specific fuel consumption with sunflower ethyl ester at 60% load

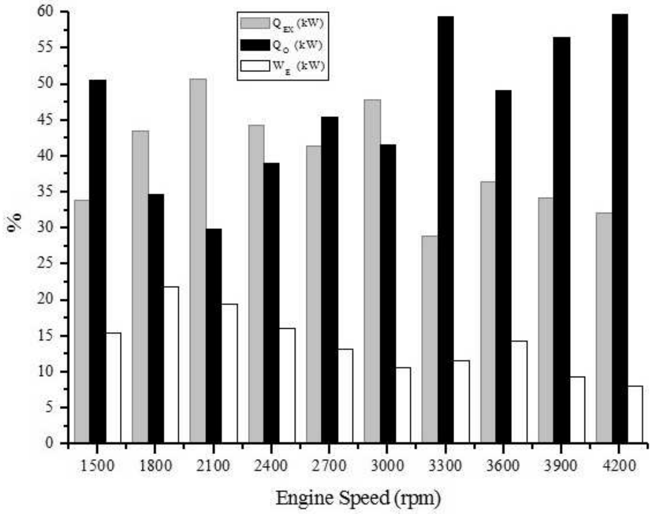

Figure 15: Breakdown of the energy at 60% load

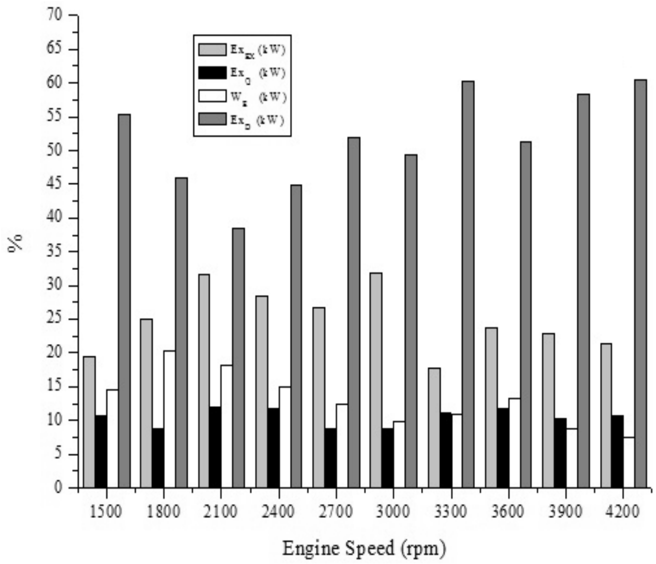

Figure 16: Breakdown of the exergy at 60% load

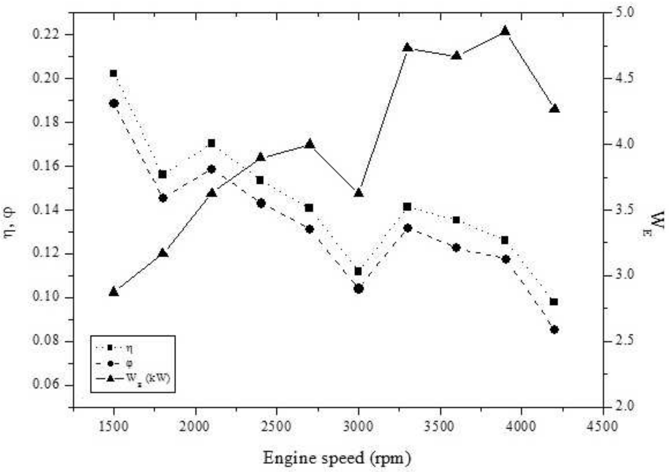

Figure 17: Effective work, energy and exergy efficiencies of the engine operating with sunflower ethyl ester at 80% load

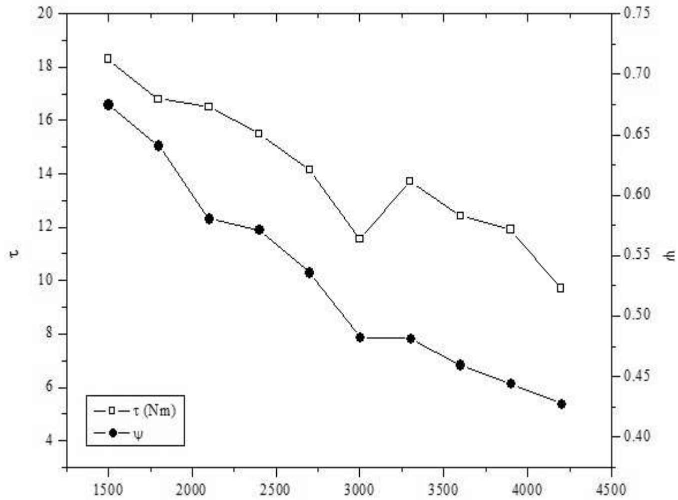

Figure 18: Torque and volumetric efficiency with sunflower ethyl ester at 80% load

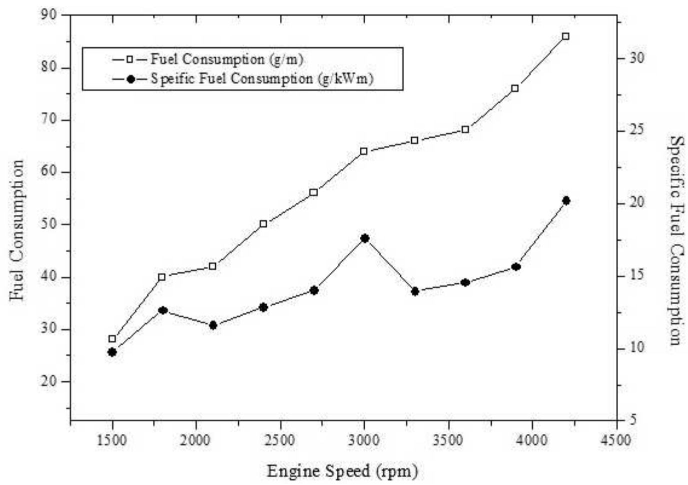

Figure 19: Fuel consumption and specific fuel consumption with sunflower ethyl ester at 80% load

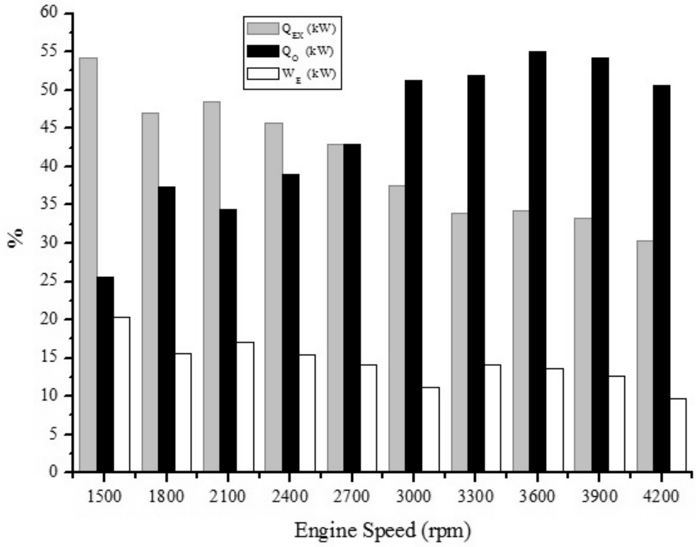

Figure 20: Breakdown of the energy at 80% load

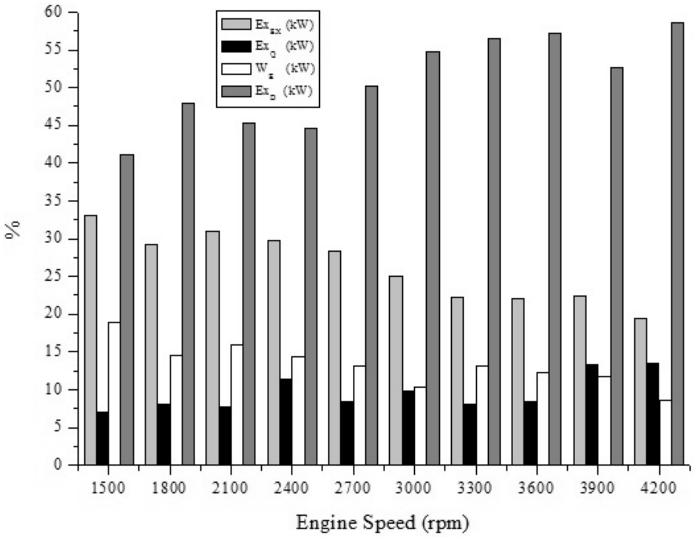

Figure 21: Breakdown of the exergy at 80% load

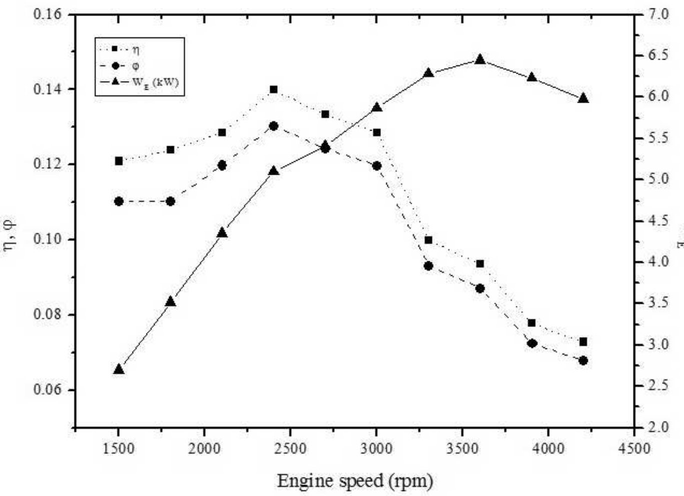

Figure 22: Effective work, energy and exergy efficiencies of the engine operating with sunflower ethyl ester at 100% load

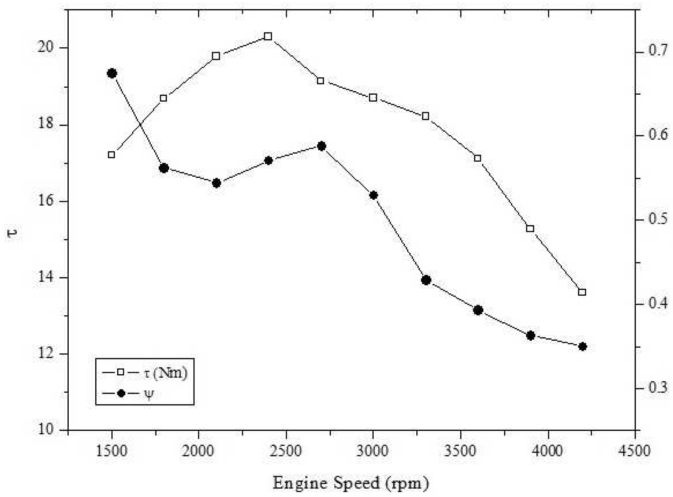

Figure 23: Torque and volumetric efficiency with sunflower ethyl ester at 100% load

speeds for all engine loads. For volumetric efficiencies, it reaches its maximum at 40% engine load and 2700 rpm (71%) and it reaches its minimum again at 40% load and 4200 rpm (0.31). It can be seen that at 20-60% engine loads the volumetric efficiency maximum is at 2700 rpm, but with 80-100% engine loads its maximum is at 1500 rpm. Generally, it can be said that volumetric efficiency always decreases after 2700 rpm and it reaches bigger values at low engine speeds.

4.5. Fuel consumption and specific fuel consumption

Fuel consumption increases with engine speed for all engine loads. It ranges from 15 (g/m) for 20% load to 180 (g/m) for 100% load. Similarly, specific fuel consumption increases with engine speed for all loads generally, and it ranges from 7.5 (g/kWm) to 30 (g/kWm) approximately.

5. Conclusion

In this study, the effects of sunflower ethyl ester were investigated on the performance of the compression ignition engine at various engine loads.

- The maximum work (6.45 kW) is obtained at 3900 rpm for 100% engine load.
- The maximum efficiency (0.26) is obtained at 1500 rpm for 20% load.
- The maximum exergy efficiency (0.24) is at 1500 rpm for 20% load.
- The maximum is at 40% engine load and 2700 rpm (0.71).

In conclusion, according to the results, it can be recommended that the engine should be operated at low engine speeds at partial loads, because at these engine speeds, energy and exergy values have the greatest values, while exergy destruction values are lower.

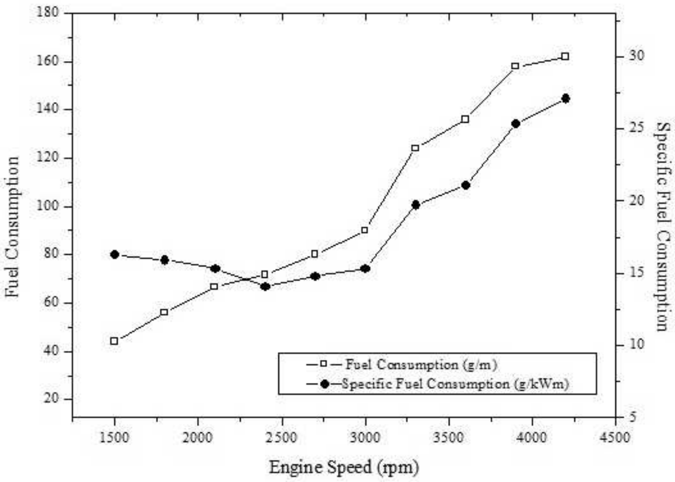

Figure 24: Fuel consumption and specific fuel consumption with sunflower ethyl ester at 100% load

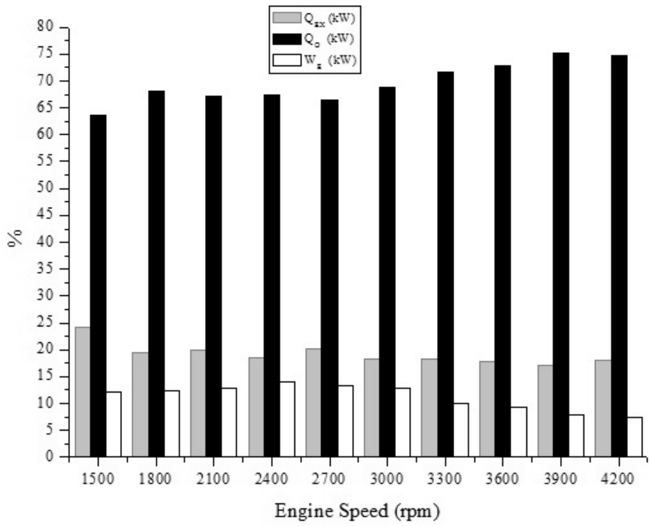

Figure 25: Breakdown of the energy at 100% load

Nomenclature

c_P specific heat capacity at constant pressure (kJ/kg)
$\dot{E}$ energy rate (kW)
$\dot{E}x$ exergy rate (kW)
h enthalpy (kJ/kgK)
LHV lower heating value of fuel (kJ/kg)
$\dot{m}$ mass rate (kg/s)
n engine speed (rpm)
$\dot{Q}$ heat (kW)
s entropy (kJ/kgK)
T temperature (K)
$\dot{W}$ work (kW)

Subscripts

D destruction
Ex exhaust
f fuel
H high
E effective work
in inputs
k system boundary
o others, environment
out outputs
p physical
$\dot{Q}$ heat
T temperature
$\dot{W}$ work

Greek letters

α fuel exergy (kJ/kg)
φ second law (exergy) efficiency (%)
η first law (energy or thermal) efficiency (%)

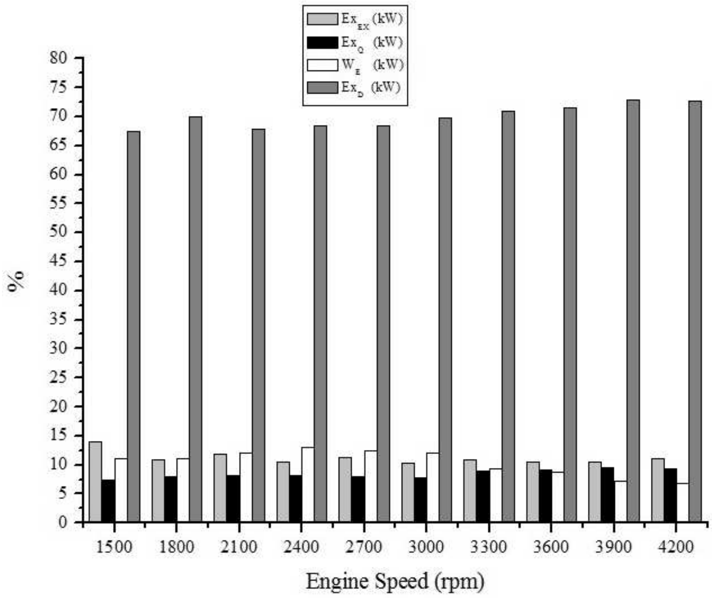

Figure 26: Breakdown of the exergy at 100% load

τ torque (Nm)
Ψ volumetric efficiency (%)

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Received 4 October 2013; revised 16 April 2014

A review on protective relays' developments and trends

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Abstract

One of the most complex disciplines in electrical engineering is power system protection which requires not only the proper understanding of the different components of a power system and their behaviours but also a good knowledge and analysis of the abnormal circumstances and failures that can occur in any element of a power system. Moreover, the rapid changing and development in relays principles as well as in their technologies are additional factors that oblige those people working in the field to expand and update continuously their knowledge. In this paper, we shed light in the evolution of protective relays since the onset of electrical energy to currently. We try also to foresee the future prospects and trends in this area.

Keywords: digital / numerical relay, protective relay, developments, trends, reliability

1. Introduction

Protective relaying is an integral part of any electrical power system. The fundamental objective of system protection is to quickly isolate a problem so that the unaffected portions of a system can continue to function. Protective relays are the decision-making devices in the protection scheme. These relays underwent, through more than a century, important changes in their functionalities and technologies. Each change brings with it odds and improvement in both technical and financial aspects. In this paper, we shed light in the evolution of protective relays since the onset of electrical energy to currently. We try also to foresee the future prospects and trends in this area.

2. Historical background

Since the early days of the onset of electrical power the need of devices to prevent or limit the undesirable events in power system have been prescribed. The history of protective relays refers to more than a century ago. Some literatures say that the first protective relay was produced in 1902 (Singh, 2007; Pathirana, 2004), others refer to 1905 (Lundqvist, 2001; Rebizant *et al.*, 2011). But whatever the date, the hard fact is that protective relays knew an important revolution since the beginning of the twentieth century. In 1909, induction disk type inverse time current relays came into practice and the concept of directional discrimination of faults was incorporated in these protective relays (Singh, 2007).

Differential relay was developed using pilot wires for conveying information from one end to the other end of the line (Pathirana, 2004). In 1923, distance relay appeared in the form of impedance. Later, the induction type mho relays with very high precision came into practice. After that, polarized dc relays with better accuracy and sensitivity were developed in 1939 (Singh, 2007; Warrington, 1968).

All of the relays developed until the 1940's were electromechanical relays. These devices achieved very high precision and sensitivity in the form of induction cup mho relays and perform well for the missions attributed to them.

The early 1940's showed the way into the development of relays using electronic devices (Singh, 2007). These relays are known as static relays or solid state relays because they didn't contain a moving parts. The advent of transistor circuits opened the door to the development of several new protection concepts like block spike comparator, phase comparator, etc.

The major advantage of these relays was that no moving parts were needed for performing their intended functions. The operating speeds of these relays were also more than the speed of their electromechanical counterparts and, their reset times were less than the reset times of electromechanical protective relays. In addition to these benefits, the solid-state relays could be set more precisely (Sachdev *et al*., 2009).

This generation of static relays became quickly very popular and found a large place in power system protection.

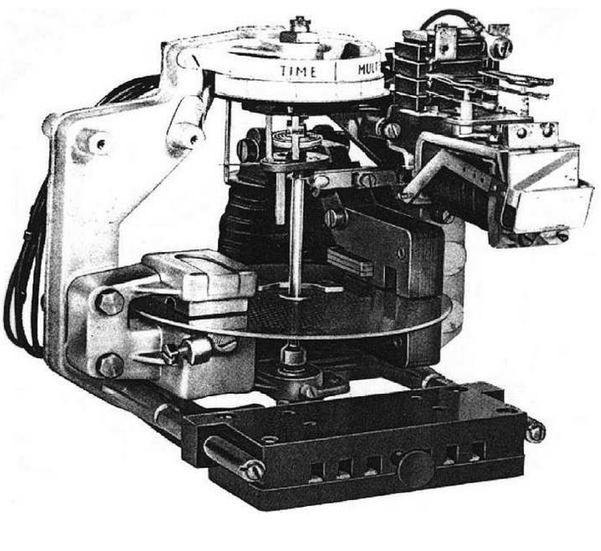

Figure 1: Example of electromechanical relay (disc type time over-current)

Figure 2: Example of a solid state relay manufactured by Crydom
(Crydom, 2012)

During the peak famous period of these solid state relays, another generation of protective devices was being set in way to see the light; it was the digital technology.

The use of Digital computers and microprocessors for protective relaying purposes has been engaging the attention of research since the late 1960s (Singh, 2004). The first serious proposals for using digital computers came from Rockefeller in 1969 (Rockefeller, 1969; Singh, 2004). Much literature reported digital relays shortly afterwards. But the first microprocessor based relays offered as commercial devices was only in 1979 (Sachdev, 1979). In that era, the efforts were concentrated to obtain a very high speed fault clearance. Different techniques and algorithms were proposed for achieving this objective. These include common hardware platforms, configuring the software to perform different functions (Sachdev *et al.,* 2009).

In the late 1980s, Multifunction digital relays were introduced to the market (Sachdev *et al.,* 2009). These devices reduced the product and installation costs drastically and has converted microprocessor relays to powerful tools in modern substations.

In 1988, the Virginia Tech research team developed the first prototype phasor measurement unit (PMU) based relay (Phadke, 2002). This technique allows measuring, beside the magnitudes of the electrical entities, the phase angles (Zhang, 2010) and could offer new information that can be used to improve the functional logic of protective relays.

In the 1990s, the notion of integrated protection and control became very popular and benefited full advantage of microprocessor technology, for protection, monitoring, control, disturbance and event handling, and communication. The relays' volumes as well as wiring were significantly reduced due to the integration of functions and the use of serial communication.

Figure 3: Modern multi-functions numerical relay manufactured by deep sea electronic
(DSE, 2014)

Perhaps the most attracting feature of these numerical relays was the ability of communication that offered new horizons for protection and protection related applications.

At the present time, there are many advanced communication techniques which can be used to improve protection, control, speed outage restoration, operation analysis, maintenance functions and planning. This communication facilities allow engineer operating, testing, maintenance and accessing real-time and historical relay information to the neighbours (Wang et al., 2002; Eissa, 2002).

The information is the basic constituent in the protection scheme. The important issue is communicating and processing information in an efficient and economical way. The key element in a communication system is the physical medium used in conveying information through the system. There are many different types of communication media such as twisted pair cable, coaxial cable, fibre optic cable and wireless communication (Ali *et al.,* 2007).

The wireless networks are by far the most popular choice for new network algorithm.

Nowadays, modern digital relays draw on the experience and technical resources of the previous series and also featured compactness and less

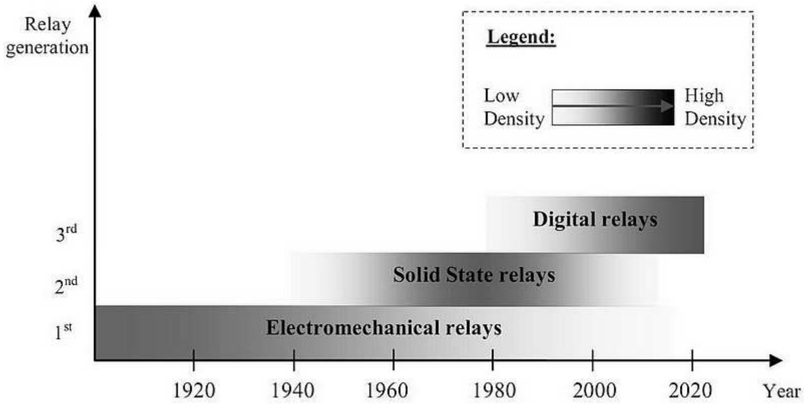

Figure 4: The different eras of protective relays

power consumption along with support for remote operation based on enhanced communication functions. The use of global positioning system (GPS) for digital measurement, especially for overhead line protection, gives very encouraging results. They are more accurate than distance relaying algorithms which are affected by inadequate modelling of transmission lines and parameter uncertainty due to line aging, line asymmetry and environmental factors (Bo *et al.,* 2000). The use of GPS technique allows providing time synchronization to$\pm$ 1μs accuracy (Radojevic´ & Terzija, 2007) a thing which proves the high precision character of this technique.

In fact, the accuracy of relays depends not only on their hardware components but also on the manner of information processing to evolve the decision signal; this is what is called the data processing algorithm or the processing method.

So, the research of the optimal method to obtain the most accurate decision in the fastest way is one major challenge in the numerical protective relay design.

Over the past two decades, the application of the artificial intelligence methods on power protection relaying (ANN, Fuzzy logic, genetic algorithms…) is under investigation. Perhaps the most wonderful aspect in artificial intelligence techniques is the ability to learn by training any complex input/output mapping and recognize the noisy patterns.

These techniques have been quite successful but are not adequate for the present time varying network configurations, power system operating conditions and events (Babu et al., 2011).

3. Performances evaluation

Electromechanical relays are still the most predominant relays in almost all countries through the world including the USA (EPRI, 2004) and Russia (Gurevich, 2012), especially for HV and EHV. Truth proves, without doubt, the effectiveness of this generation of protective relays. However, during the past 15-20 years, there has been a widespread displacement of EMR by microprocessor-based relay protection devices (Gurevich, 2012). This transition from the electromechanical to the numerical relays can be justified by the large flexibility and the wonderful features such as:

- Multifunction
- Compactness
- Communication
- Reduced volume and wiring
- The low cost.

While all these functionalities and characteristics of numerical relay make it a magic solution for protection system; some specialists and experts expressed their anxieties about the reliability and the lifetime of these new relays. Thus, the lifetime of old electromechanical relays can exceed 40 years, some of them were performed in service for more than 50 years. Whereas that of the numerical relay is estimated between 10 - 15 years (Gurevich, 2012). This is a result of the ageing of their electronic components, bringing on changes in their parameters, during their lifetime. For example, the service life of electrolyte capacitors, which are widely used in microprocessor based relays, does not exceed 7–10 years (Gurevich, 2009), and this is under favourable conditions of temperature and humidity.

From the viewpoint of reliability, a statistical study (between 2000 and 2009), posted by A.N. Vladimirov., Deputy Head of Relay Protection Department of Central Dispatch Service of UES of Russia, showed that the reliability of microprocessor based relay is about 60% less than that's of electromechanical relay (Vladimirov, 2009; Gurevich, 2010).

The high accuracy and precision of numerical relays (NR) compared with electromechanical relay (EMR) are counterbalanced by its weak immunity against electromagnetic perturbations.

Table 1 shows a comparison between the different generation relays.

The previous cited problems of NR are the important titles' debated in this field. But whatever the matter, we guess that these problems are issues

Table1: Comparison between the different generations of protective relays

Relay type feature	*Electromechanical*	*Solid state*	*Digital*
Accuracy & sensitivity	Good	Very good	Excellent
Lifetime	Long	Short	Short
Undesired operating	Almost never	Possible	Possible
Reliability	High	Good	Moderate
Discrimination capability	Low level	Good	Excellent
Condition monitoring	No	No	Yes
Multifunction	No	Limited	Yes
Data communications	No	No	Yes
Remote operation	No	No	Yes
Disturbances immunity	High	Low	Very low
CT burden	High	Low	Low
Parameters setting	Difficult	Easy	Very easy
Range of settings	Limited	Wide	Very wide
Self-diagnostics	No	No	Yes
Metering	No	No	Yes
Event archiving	No	No	Yes
Size	Bulky	Small	Compact
Visual indication	Targets	LEDs	LCD

of risk control. And once the risk is well identified and properly assessed, it is just enough to take it into account and to plan making the necessary actions in the good instants. For example, if we are sure enough that the lifetime of a digital relay is 10 years, we must foresee its change after ten years minus epsilon , we should, also, be careful in its last years of service.

So, after identifying the weak points of the protective relay; it will be clear where one must focus the efforts to reduce the failure risk and, consequently, improve the reliability of the relay (Abdelmoumene & Bentarzi, 2012). The use of the redundancy technique (back up element) allows a significant reduction of failure rates, and hence improving the reliability of the considered protection system (Abdelmoumene & Bentarzi, 2012).

Nuclear power plants (NPPs) traditionally relied upon analogue instrumentation and control systems for monitoring, control, and protection functions. With a shift in technology from analogue systems to digital systems with their functional advantages (e.g., fault-tolerance, self-testing, signal validation, and process system diagnostics), plants have begun such replacement.

However, digital systems have some unique characteristics, such as using software, and may have different failure causes and/or modes than analog systems; hence, their incorporation into NPP probabilistic risk assessments (PRAs) entails special challenges (U.S.NRC, 2011).

At any rate, it is inevitable that power plants will slowly move toward newer technology. In fact, this movement toward the use of digital/numerical type relays has already begun. In 2004, some U.S. nuclear plants had already installed digital relays for selected applications (EPRI, 2004). Japanese and French power plants had also begun testing these new technologies in their nuclear power plants (NPPs) (IAEA, 1999; Hashemian, 2011).

4. Concluding remarks

Throughout this paper, an historical background of protective relays has been presented. The latest developments and trends have been also introduced and discussed whether for hardware and technology aspect or software and method aspect. The performance evaluation and comparison between the different relays generations have been done in order to bring out the strong and the weak points of each relay type. The relatively low reliability level of new numerical relays constitutes the major worry expressed by many experts in the protection field. In our opinion, the wonderful achievement in performance and functionalities enhancement brought out in numerical relays must be completed by the research to increase significantly the reliability level and mastering the risk assessment.

This paper is the result of great efforts during a long time of research in specialized literatures to establish an exhaustive document which resumes the main highlights in protective relay's developments and trends.

Acknowledgements

The authors acknowledge the immense help received from the scholars whose articles are cited and included in the references of this manuscript. The authors are also grateful to authors / editors / publishers of all those articles, journals and books from where the literature for this article has been reviewed and discussed.

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Received 23 July 2013; revised 21 March 2014

General aspects of carbon dioxide as a refrigerant

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Abstract
Carbon dioxide is an innocuous refrigerant for the environment. It is a substance of current interest in the refrigeration area. Its good thermodynamic and heat transfer properties have placed it in an excellent position for substituting refrigerants that contribute to global warming. This paper describes carbon dioxide as a refrigerant, the main characteristics that have made it a substance of current interest, its applications in subcritical and transcritical cycles, and a general vision of its usage at international level. Moreover, this paper presents the disadvantages of using this refrigerant and the upgrades made by the scientific community in order to improve the performance of those systems that work with this fluid. This paper is a reference for those interested in having a wider vision of frigorific technology based on carbon dioxide as a refrigerant.
Keywords: *CO_2, low GWP, COP, refrigeration, air conditioning*

1. Introduction

In recent years, our planet has faced two major problems with refrigerants where ozone depletion potential (ODP) and global warming potential (GWP) are important factors to consider. The replacement of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) for hydrofluorocarbons (HFCs), which have some potential for the destruction of stratospheric ozone (low ODP), was a step forward. However, this did not help global warming as a direct contribution by these refrigerants remains. It is for this reason that the scientific community is considering additional natural substances and other refrigerants with minimum GWP and zero ODP.

The use of CO_2 as a refrigerant, concurrent with mechanical refrigeration began in the mid-century 18^{th}. In 1744, Joseph Priestley dissolved carbon dioxide in water, which resulted in a decrease in the temperature of the liquid, suggesting suitable thermodynamic properties for refrigeration. Years later, William Cullen at the University of Glasgow studied the evaporation of liquids under vacuum. Under a number of experimental conditions, ice could be produced with evaporation.

Oliver Evans in the 19^{th} century proposed that refrigeration could be achieved using mechanical vapour compression, and Alexander Twining proposed the use of CO_2 as a refrigerant in an 1850 patent (Bodinus, 1999). While this work was ongoing in Europe, Thaddeous S.C. Lowe in America (circa 1867) described refrigeration using CO_2 in his patent (Thévenot, 1979), and a subsequent machine was developed by Carl Linde (Aarlien, 1998). Five years later, Franz Wildhausen in Braunschweig patented a compressor using CO_2, later licensed for development by J&E Hall that lead to the development of the first double-stage compressor (Cavallini and Steimle, 1998). The Sabroe company was first to develop a household refrigerator and at the end of the 19th century, CO_2 as a refrigerant reached its peak being used in air conditioners and refrigerated displays. Although ammonia and sulphur dioxide were capable refrigerants, they were also toxic and flammable. This positioned carbon dioxide as the best alternative for the future.

Carbon dioxide dominated as a refrigerant worldwide in the early part of the 20th century until the development of the first synthetic refrigerants. The new synthetics were marketed globally offering cooling with smaller units with greater efficiency. This lead to the decline of carbon dioxide as a refrigerant in the 1930s. The use of CO_2 as a refrigerant essentially ceased in the 1950's, since CFCs dominated the worldwide market.

For almost half a century, CFCs dominated as refrigerants. Following the work by Mario Molina and Sherwood Rowland in the 1970's which showed destruction of the stratospheric ozone and the production of holes over the Antarctic. The scientific community promoted the use of alternatives such as hydrofluorocarbons (HFCs) that were not reactive. Later these were judged as unfavourable alternatives that would contribute to global warming and industrialized countries within the European Union initiated processes to eliminate these refrigerants in compliance with the objectives established by the United Nations (Natarajan, 2008). With these events, a resurgence and interest in past refrigerants initiated with expectations of not harming the environment. Refrigerants less than 150 GWP are desirable, and carbon dioxide is one substance meeting these criteria (Calm, 2008).

Without the detrimental effects of CFCs and HCFs, Gustav Lorentzen in 1980 patented an application using carbon dioxide called transcritical cycle (Lorentzen, 1990). Figure 1 illustrates the refrigeration cycle with one enhancement: the inclusion of a heat exchanger (indicated with the number 12), known as an intermediate exchanger that produces an increase in energy performance.

According to current world wide environmental awareness, natural refrigerants are one of the main focuses of attention for the scientific community. Hence, in view of the fact that carbon dioxide is one of the oldest natural fluids with the most recent re-utilization, this paper presents a modern situation and the tendencies in the use of this substance as a refrigerant, since nowadays it is becoming an interesting option in the areas of refrigeration and air conditioning again.

The following sections consider the advantages and disadvantages in the use of carbon dioxide as a refrigerant. Physical properties, technologies and subcritical and transcritical modes are also considered.

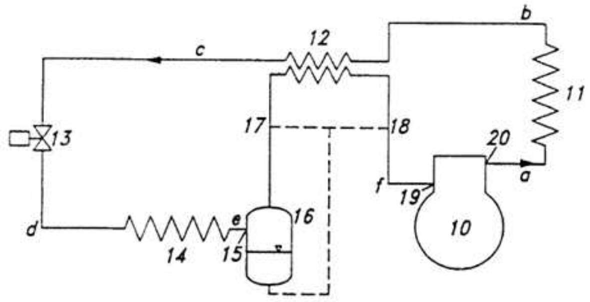

Figure 1: Transcritical cycle with intermediate heat exchanger proposed by Gustav Lorentzen (original schema)
Source: Lorentzen (1992)

2. CO_2 in subcritical and transcritical cycles

Cold generation, whether for refrigeration or air conditioning, is mostly achieved through vapour compression refrigeration. Cycles used to achieve efficient compression are classified in respect to their critical point: subcritical and transcritical. Subcritical cycles run below critical point of the working fluid in which transcritical is above. Carbon dioxide can be used in both cycles, however, when working as subcritical it does it as a secondary fluid and in this case, the primary fluid is another substance. A diagram of pressure enthalpy for both cycles is presented in Figure 2.

The COP defines the efficiency of a refrigeration cycle in subcritical and transcritical systems. The COP is the ratio between the energy absorbed in the evaporator and the work required by the compressor. In this context, when a carbon dioxide system operates in a subcritical cycle, the main constraint for the COP is sump temperature. According to the application, different performance values can be achieved in these cycles. Later, performance values of subcritical carbon dioxide systems will be described for each application. For a transcritical cycle, the limit of COP is the temperature of the refrigerant at the outlet of the evaporator. Lower evaporating temperature increases the COP of the system (Neksá, 2002). In this mode, several configurations have been developed in order to improve the COP, this includes the inclusion of an internal heat exchanger, a turbine, an ejector or a vortex tube, and expansion stages. Pérez-García *et al*., (2013) present some configurations where the carbon dioxide is used in transcritical cycle, in its work,

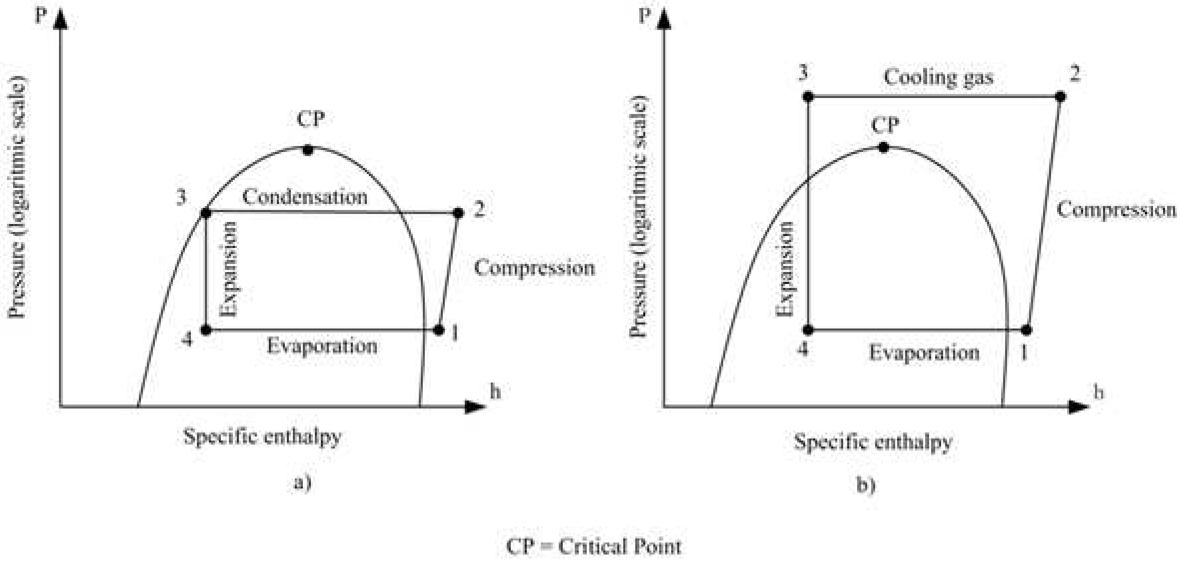

Figure 2: Vapour compression cycles: a) subcritical b) transcritical

the transcritical system has an energetic performance from 2.01 in a single cycle to 2.6 when the cycle is modified using a turbine. Sarkar (2010) also shows another configuration where the use of an ejector in a transcritical cycle causes an improvement in the performance of the system around 16% in respect to the single cycle. This enhancement can be obtained by increasing the refrigeration capacity.

Figure 3 shows how the COP is increased in the transcritical cycles by making use of different elements like a turbine (TC), and intermediate heat exchanger (IHXC) and an ejector (EC). All of them were compared with the simple cycle (SC) in order to compare the increase in the energy efficiency of the cycle.

Due to this characteristic, it is one of the applications of CO_2 as a refrigerant in heat pumps, in which the energy performance is really competent compared with the use of synthetic and high GWP fluids. A description of the use of the CO_2 heat pumps showing adequate results of performance, this type of facility can be found in the work of Neksá *et al.,* (1998, 1999). The authors demonstrate an excellent performance of the heat pump in which a COP of 4.3 is reached for the analysed prototype. This is for cold weather like in Oslo. Another significant advantage of transcritical systems in heat pump mode compare to conventional systems is that hot water up to 90°C can be produced without operational difficulties.

When carbon dioxide is used in a subcritical cycle, pressure and operating temperature range is limited in which the evaporation of a liquid is at least -55°C and the condensation is at maximum 30°C. There are three common applications of CO_2 in a subcritical cycle: as secondary fluid, cascade and mixed systems. When carbon dioxide is used as a secondary fluid, it is pumped and not compressed; while a cascade system uses a primary fluid that allows condensation at temperatures below 0°C. The main application of this system is to be cooled to low temperature evaporating carbon dioxide below -30°C.

Mixed systems combine the two previous applications, and are very useful in places such as supermarkets where two ranges of temperatures (cooling and freezing) are required. Here the medium temperature (cooling) services operate with CO_2 as a

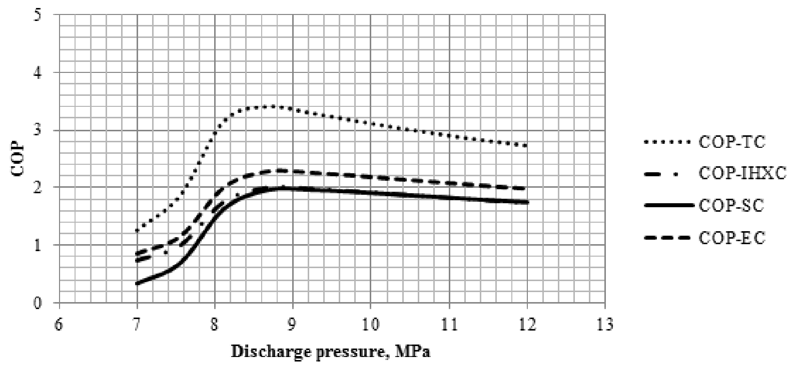

Figure 3: Increase in COP for some configurations used in transcritical cycles

secondary fluid and low temperature (freezing) services do it using direct expansion evaporators. In transcritical cycles, the fluid is not condensed where the pressures are varying from 7.31 MPa up to 12 MPa as the phase exceeds a critical point (31°C and 7.3 MPa) and the process becomes a sensible cooling of the gas. In cold weather, the energy consumption in transcritical systems is relatively low, while for hot climates efficiency decreases due to the thermodynamic properties and heat transfer which this fluid has.

Figure 4 shows a comparison of the energy consumption during 37 weeks between a potential system and a cascade system using R-410 and R-744 (CO_2) against the consumption of a system that uses R-404A, which is one of the conventional refrigerants used in supermarkets in Denmark (Danfoss, 2008). The transcritical systems energy is lower compared with other fluids for the same operating conditions, which is the reason why the use of transcritical systems is a highly competitive choice to replace conventional systems in Northern Europe.

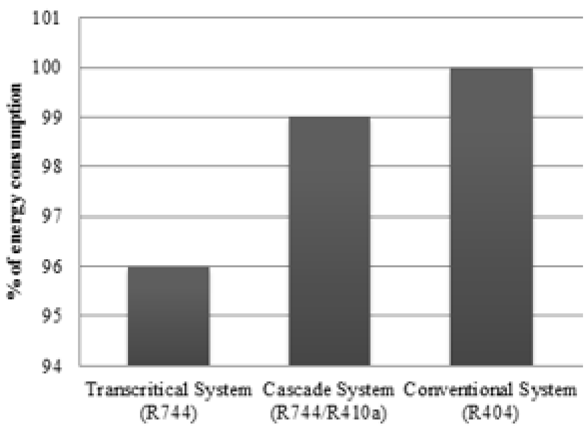

Figure 4: Comparison of energy consumption between transcritical and cascade systems
Source: *Danfoss (2008)*

In general terms, it is concluded that CO_2 applications in the cold generation are many. Among these applications CO_2 is found in frigorific facilities as secondary fluid, in automotive air conditioning, vending machines and supermarkets (Bensafi and Thonon, 2007).

3. CO_2 features

One of the characteristics that CO_2 has in comparison with other refrigerant fluids is the operational pressure which is superior to all other conventional refrigerants and those from a new generation (10 times higher than that of the ammonia, R-404A, R134a, R-22, R-12 and HFO-1234yf). This particularity makes it necessary to use especial equipment for its handling. However, at the same time, it offers advantages that no other refrigerant fluid has. The high pressure turns it in a high density gas according to its thermophysical properties. This causes it to obtain a major refrigerant effect with little mass circulating through the vapour compression system.

In a frigorific system, the ideal option is that oil and refrigerant fluids are completely miscible one in the other as this allows that the oil coming from the compressor circulates through all the circuit and returns back to the compressor 100%. In this context, the oil, type POE (polyolester), meets this characteristic. Notwithstanding, it has been found a notable diminishing in the coefficient of heat transference close to the pseudocritical temperature (Zingerli and Groll, 2000). This is why Chaobin Dang *et al.,* (2007) have done research with oil, type PAG (polyalkaline), which is partially miscible, they found that the diminishing in the coefficient of heat transfer is, principally, due to parameters like: the temperature, mass flow rate, and the piping diameter, in which the major loss of heat transfer is when the diameter of the piping decreases.

3.1 CO_2 advantages

Carbon dioxide has a benefit in being more economical. Take into consideration that it is less expensive to produce in comparison to synthetic refrigerants, and that most alternatives require additional safety and physical transport regulations.

Its thermodynamic and transport properties are excellent. In addition, it is environmentally friendly; it is not flammable and relatively chemically inert. Some of the important physical properties of CO_2 are shown in the phase diagram in Figure 5.

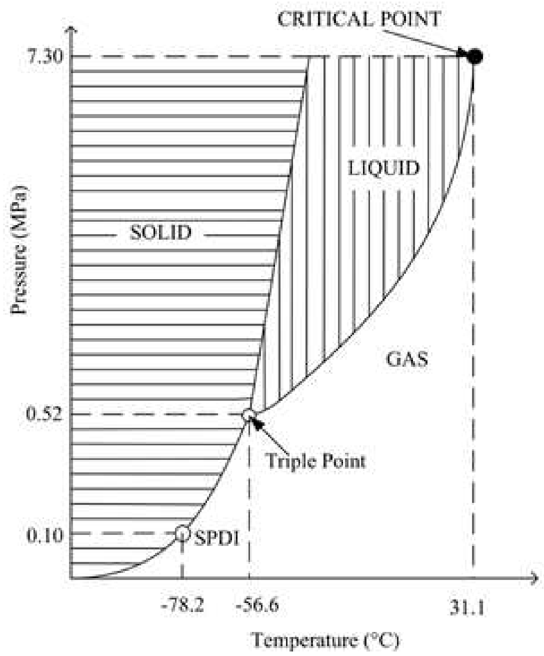

Figure 5: CO_2 phase diagram

Two of them are indicated as the triple point and the critical point, a third is indicated as SPDI, the sublimation point of dry ice that occurs at atmospheric pressure and at a temperature of 78.2°C. The critical point which takes place at a temperature that is easily attainable in environmental conditions in warm places. The critical temperature and pressure conditions shown in Figure 5 cause the rejection of heat to the environment and does not involve a condensation of fluid work (Cavallini, 2004). In the cold generation by vapour compression, it is desirable to manage the working fluid with inlet pressure to the compressor that is equal to or greater than the atmospheric one, so that air does not infiltrate into the system. Carbon dioxide meets this basic characteristic for having more than 0.52 MPa inlet pressure. On the other hand, Table 1 presents the properties of several refrigerants compared to CO_2.

Here is possible to see the notable difference of CO_2 regarding the volumetric capability of heat, which implies using a less quantity of refrigerant mass than in any other system in order to achieve the desire refrigerant effect, and by this to overcome to all its competitors. It is also remarkable that in regard to the environmental aspect, it is the second best after ammonia. Nonetheless, ammonia is toxic for human beings and therefore, respecting toxicity – CO_2 is a better option.

3.2 Thermodynamic properties

The thermodynamic properties of fluids are essential for the design of equipment, particularly in relation to the energy requirements, phase equilibria, and the size decision thereof (Kim *et al*., 2004). In the transcritical region, the enthalpy and the entropy decrease along with the temperature in sudden changes close to the critical point. Pressure influences the enthalpy and the entropy above the critical temperature whereas its effect is little under it. The main characteristic that will condition the design of a facility using CO_2 is the high pressures to which the system operates. Density is another important factor in CO_2; in high densities, the required displacement by the compressor and the diameter of the connection piping is reduced. This represents a small advantage in view of the fact that if the diameters of the piping in conventional systems are small, as a result, small system designs will be obtained.

Surface tension in refrigerants fluids influences nucleated boiling and two-phase flow characteristics. A low surface tension reduces the overheating required for nucleation and growth of bubbles of steam, which will improve heat transfer. The surface tension of the CO_2 is low compared to other refrigerants. It has a coefficient of heat transfer between 60 and 70% higher than conventional refrigerants except for ammonia (Padalkar and Kadam, 2010). The volumetric capacity for CO_2 is 3 or 4 times higher than for other refrigerants. Therefore, CO_2 systems require less CO_2 as well as a smaller compressor, heat exchangers and pipeline. The main energy characteristics of these refrigerants compared to CO_2 are shown in the Table 2.

In Table 2, it can be see a low value of latent heat for CO_2; this means that CO_2 needs the least

Table 1: Properties of several refrigerants compared to CO_2

Numerical assignment	*Boiling point, K (at 0.1MPa)*	*Critical temperature, K*	*Critical pressure, MPa*	*Volumetric heat capacity, kJ/m^3*	*Density,Kg/m^3 (at 20°C and 0.1MPa)*	*Safety group*	*ODW/GWP*
R-134a	246.85	374.2	4.12	2868	4.336	1	0/1 300
R-290	231	369.8	4.31	3907	1.865	2	0/3
R-744(CO_2)	194.6	304.1	7.38	22545	1.839	1	0/1
R-22	232.4	369.1	4.98	4356	3.651	1	0.05/1 700
R-717	239.8	406.1	11.42	4382	0.716	2	0/0
R-410A	325.85	343.3	4.85	6753	3.062	1	0/1 740
R-407C	229.35	359.2	4.70	4029	3.639	1	0/1 610

1. Security group: negligible toxicity, non-flammable.

2. Safety group: toxic, flammable, or both

Table 2: Comparison of other properties of CO_2 used in commercial refrigeration fluids
Source: USDOE (2003)

Feature	*R-502*	*R-507a*	*R-404a*	*R-744 (CO_2)*
Cooling capacity (kJ/m^3)	4683	5227	5052	22545
Latent heat (kJ/kg) a 25°C	128.1	136.2	140	119.7
Energy performance (COP)	3.05	2.949	2.876	1.835
Specific volume (m^3/kg) a -10°C	0.043	0.0543	0.0453	0.0142
ODP/GWP	0.334/4657	0/3300	0/3260	0/1

amount of energy to change the phase, this is directly linked to its thermodynamic properties and certainly its low latent heat represents a disadvantage, since for a refrigerant the greater is its latent heat of vaporization, the greater the heat absorbed per kilogram. Therefore, if there is a high value of latent heat, cold production is high and the mass flow will be less.

3.3 Environmental aspects

The GWP of a substance only quantifies the contribution to climate change from a greenhouse gas when it spreads directly into the atmosphere, which could be termed as direct greenhouse effect. Refrigerant fluids fume enters the atmosphere due to leakage in plants caused by losses during peacekeeping operations or by the non-recovery of the refrigerant when the facility is not used. In addition to the direct effect of the refrigerant in facilities, there is also the indirect effect linked to energy consumption. This indirect effect is not exactly a feature of the fluid, but that depends on the facility, amount and type of energy consumed. Thus, this occurs as a result of the energy consumption of the facility if the energy used comes, totally or partially, from the combustion of fossil fuels that emit CO_2 into the atmosphere. The parameter that measures both effects as mentioned is the Total Equivalent Warming Impact (TEWI) and its definition by means of mathematical expressions is (ARIAH 2012):

$$TEWI = GWP * m * L_{anual} * n + GWP * m * (1 - \alpha_{recuperado}) + E_{anual} * \beta * n \quad (1)$$

Being the first two terms of the equation the direct effect and the third indirect effect. Different authors have lectured on the data needed to obtain the value of the TEWI, and may conclude that this parameter is not calculated for a refrigerant, but for a given application (Sand *et al*., 1999; Fischer, 1997):

- Type of refrigerant used in the application, to get the value of the GWP.
- The amount of refrigerant mass released to the atmosphere during the operation of the system at all its life. (L_{anual}, in kg).
- Useful life of the system (n, in years).
- Refrigerant charge (m, kg).
- Recovery factor (α from 0 to 1).
- Energy consumed annually in the operation of the installation (E_{anual}, in kWh per year).
- Indirect emission factor (β, in kg of CO_2 per kWh).

Based on this definition, for a facility that operates 365 days a year and that spends 7 kWh/day with a leakage ratio of 0.25 and a recovery percentage of 20%, the TEWI for facilities that use different refrigerants is the one shown in Figure 6 (*Australian Institute of Refrigeration Air Conditioning and Heating*, 2012).

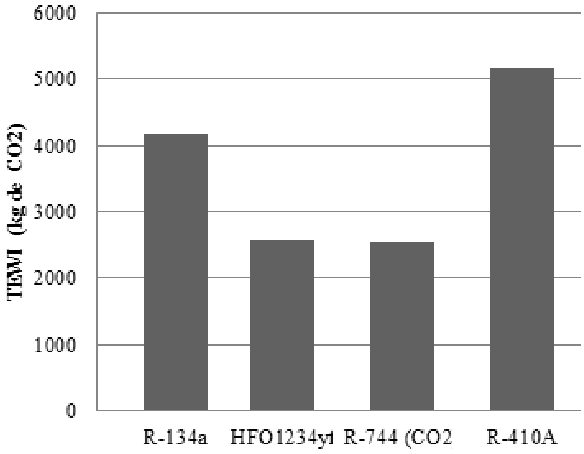

Figure 6: Comparison of the TEWI under the same conditions and considering a similar recovery factor

Therefore, facilities operating with CO_2 under the conditions set out in Figure 7 emit less CO_2 both evaluating the direct effect as indirect, proving to be the only drawback, the high pressures of work. Also, another important feature of these kinds of facilities is their poor efficiency in warm environments. Hinde *et al*., (2008) mentioned that the most practical application might be using CO_2 in cascade systems or using it as secondary fluid. Aprea *et al.,* (2012) researched on direct and indirect contribution of having CO_2 as refrigerant, and they pointed out that this contributes indirectly to CO_2 emissions in greater quantity than their own R-134a. Nevertheless, this does not happen in every case, the authors refer to the operation conditions in which CO_2 is a viable alternative in a transcritical cycle, such conditions are at ambient temperature between 25 and 30°C and an evaporation temperature of 0 and 5°C.

In a study conducted by Kruse (2000), it is mentioned "in the same way" applications in which CO_2 is an alternative as a refrigerant to minimize the TEWI. The authors also mention that the use of CO_2 in a potential cycle is a good choice as a substitute for conventional systems. The drawback arising with this type of system is the high cost of the operating pressures. On the other hand, in Germany, there is a study relative to the direct and indirect emissions of greenhouse gases of the fluids used in supermarkets, (Rhiemeier *et al.,* 2008) in this study showed different results, one of them is presented in Figure 7. The presented emissions are annual and measures per linear meter deeming 6.15% of loss of refrigerant.

Figure 7 can be seen as the direct contribution of CO_2 which is minimal, while the indirect contribution is significant and strengthens the study done by

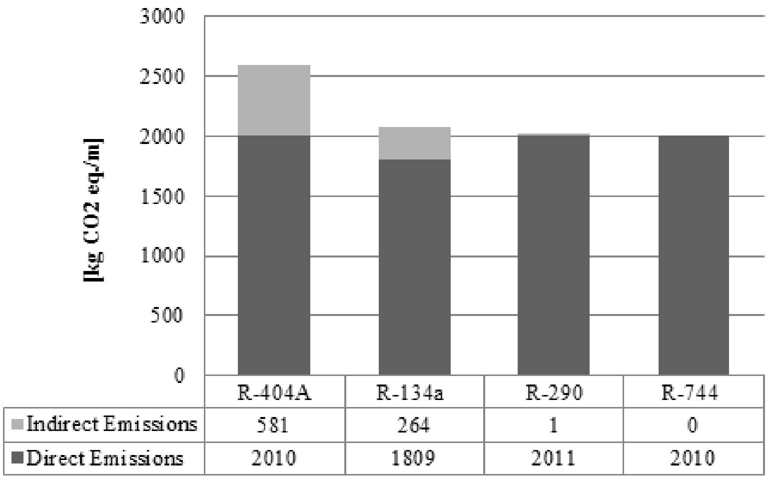

Figure 7: Direct and indirect emissions in kg of CO_2 systems in simple cycle
Source: *Rhiemeier et al. (2008)*

Aprea *et al.,* (2012). However, adding the direct and indirect effects, the TEWI of systems that use R-134a is slightly above the systems that use CO_2 by using transcritical systems representing a viable alternative, since the negative contributions to the environment are lower than those of the refrigerant R-134a.

3.4 Energy aspects

Although the energy performance of facilities operating with CO_2 in cooling mode are below those that do so with HFC´s, when CO_2 is used in heat pump mode (Brian et al., 2011), performance competes adequately with respect to conventional refrigerants. It has been shown that during cold weather, facilities using CO_2 such as refrigerant in heat pumps are even more efficient which actually make use of refrigerants, due to its excellent heat transfer properties. Figure 8 shows a comparison of the results of the simulation of a low-temperature commercial refrigeration cycle. It shows that the energy behaviour of the refrigerant fluids R-502 and its substitutes R-404a and R-507a is very similar,

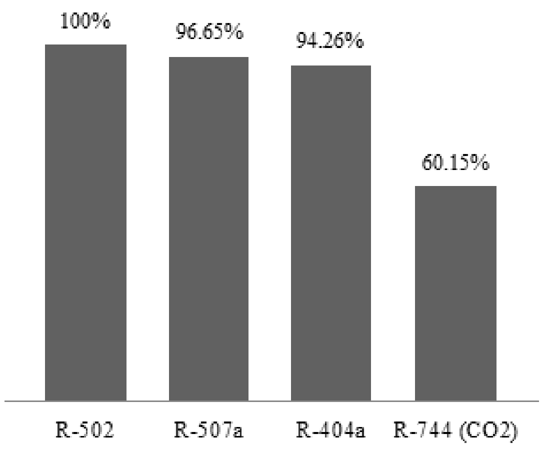

Figure 8: Comparison to subcritical cycle for refrigerants conventional and potential for CO_2, Tev = -10°C, Tcond = 35°C

while using the CO_2, the performance drops considerably when operating at the same conditions.

In automotive air conditioning CO_2 is considered as an option and when comparing it with R-134a, it is reported as acceptable. However, the automotive industry has tilted for a mixture known as HFO-1234yf, although nowadays there are still some doubts about the safety of this fluid due to its flammability.

Germany, at the end of February 2013, announced that it will not use this refrigerant in their automotive brands. Companies such as Volkswagen, Audi, BMW and Daimler, have opted to conduct research to improve the transcritical cycles and apply them to their vehicles, arguing that the HFO is not safe enough for its vehicles using it (www.r744.com/news/view/3957). The energy aspect, on domestic air-conditioning, CO_2 competes with the R-134a which is still used in Europe, while in the United States it is being displaced by the HFO-1234yf.

As part of a new technology that is being introduced in the developed countries CO_2 is energetically compared with the two previously mentioned fluids (R-134a and HFO-1234yf) by way of exemplifying the potential of this refrigerant. Various laboratory tests were performed and Figure 9 shows these results, showing a comparison of the achieved yields of these 3 fluids under similar operating conditions.

On the other hand, Figure 10 shows the energy consumption of the compressor on each system for the different refrigerant fluids.

It is noted how the power consumption of a compressor that uses CO_2 is lower in certain temperature ranges and certainly these values show a set of points at the end of which the consumption is similar.

3.5 CO_2 disadvantages

In the refrigerants used in the industry, only ammonia is lighter than air, which means that in case of leakage this moves above the air leaving people who are operating facilities vulnerable (only if the leak is higher and the amount of refrigerant is excessive). Nonetheless, industry has presented technological advances on security with refrigerants heavier than air and also toxic. It is clear that CO_2 as any other refrigerant is not an ideal substance to be consider in refrigeration, however, from an environmental point of view it is a dormant option that can be consider for its use.

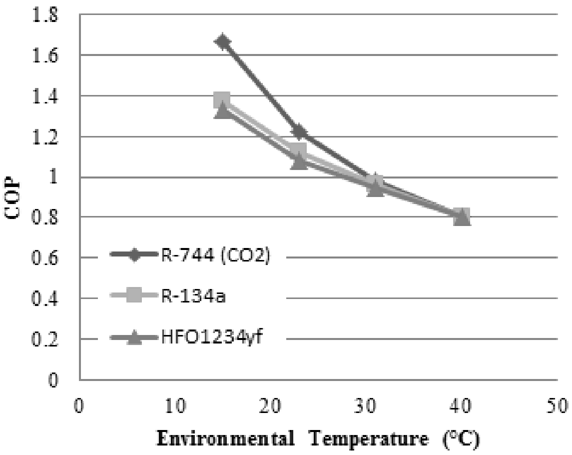

Figure 9: Energy efficiency of 3 systems that use R-134a, R-744 and HFO-1234yf
Source: *Kimura et al. (2010)*

In air conditioning, the most commonly used fluids are currently R-407C, R-410A and R-290. CO_2 can be used in this application and in fact, the use of this fluid has increased mostly in the countries of Northern Europe. Figures 11 and 12 show a comparison of the energy performance of these fluids for heat pump and refrigeration modes.

Table 3: Some disadvantages of CO_2 as a refrigerant

High working pressures.
Limited flexibility.
Minimum evaporation temperature: - 56°C.
Condensation temperature maximum: 31°C.
More expensive facilities operating with conventional refrigerants.
Heavier than air. In case of escape, the CO_2 is coupled to ground level and displaces air.
In case of leaks, there is no warning based on smell (odourless).

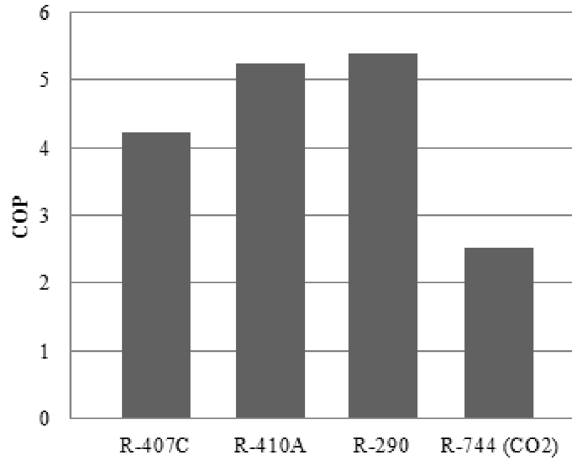

Figure 11: Energy efficiency of cooling for different fluids. TEV = 0°C, Tcond = 30°C

As it can be seen the energy performance of the cycle transcritical with CO_2 is below the other systems, this is because of the condensation temperature which is approaching the critical point of the fluid, and the amount of energy rejected is increas-

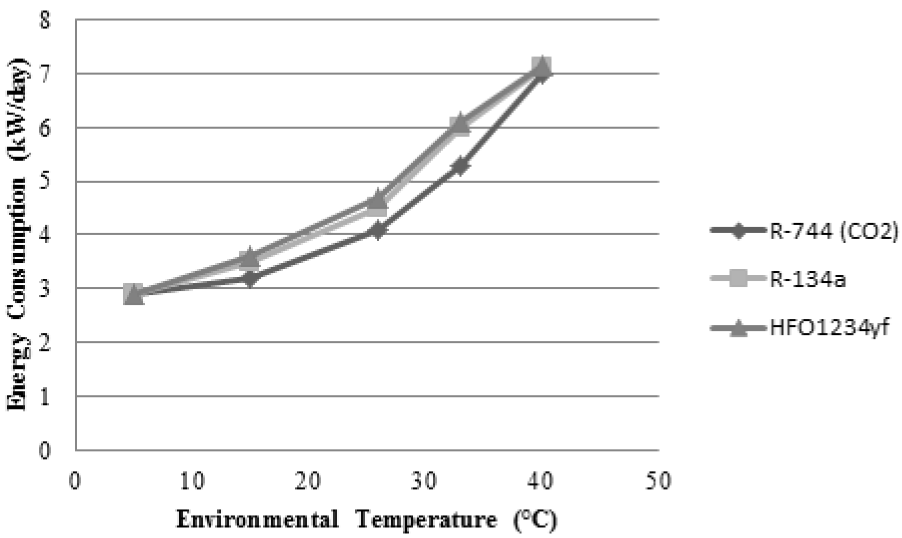

Figure 10: Power consumption of systems for different fluids
Source: *Kimura et al. (2010)*

ing. This is reflected in a reduction of the heat transfer and requires a surface contact area larger to maintain a constant heat transfer, which without doubt directly affects the performance of the cycle.

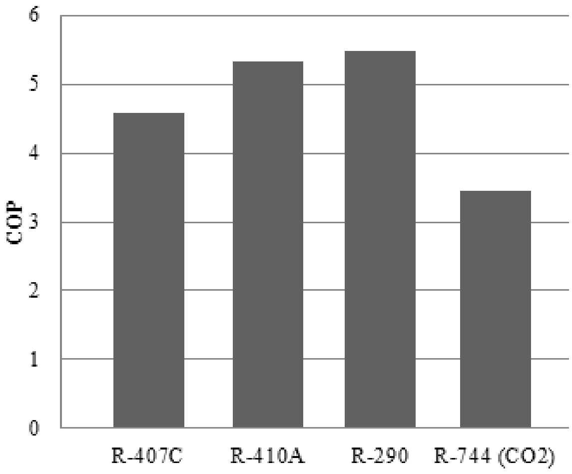

Figure 12: Energy efficiency of heat pumps for different fluids. TEV = 0°C, Tcond = 30°C

4. CO_2 applications worldwide

Refrigeration with CO_2 covers a wide field of application ranging from the industrial sector, transport, to the commercial sector. In the industrial sector, CO_2 refrigeration systems are used in the processes of extraction of heat in the dairy industry and soft drinks, amongst others (where companies such as Nestle, Coca-Cola, Mc Donalds and Unilever are present).

In the field of transportation, this refrigerant presents interesting results in automotive air conditioning (Jing-yang *et al.,* 2003). Is worth mentioning that in air conditioning, the use of CO_2 is still more extensive because in this area the fluid is highly competitive and even better than any of its competitors due to its excellent heat transfer properties. Heat pumps are mainly using CO_2 technology. As technology advances, more compact facilities operating with CO_2 are found than those used some decades ago.

Today, technology has advanced so much that it is possible to have refrigeration systems by vapour compression operating with CO_2 in cars. Due to their thermodynamic properties, at the last Olympic Games of Beijing 2008, CO_2 was replacement used for buses (http://conf.montrealprotocol.org). In Germany in 2009 the transport company Berliner Verkehrsbetriebe (BVG) set the operating of buses in the city of Berlin using CO_2 as refrigerant in the air conditioning system (http://www.bvg.de).

In shopping malls, refrigeration equipment using CO_2 as a primary and secondary refrigerant has shown good results to be implemented in refrigerators for the conservation of plant products (http://www.achrnews.com).

In 2009, Pick n' Pay with help of GIZ Proklima, installed two cascade systems with ammonia and carbon dioxide (Johannesburg and Cape Town) in two of its supermarkets. In 2011, Makro South Africa installed cascade systems of ammonia and carbon dioxide in three out of fifteen of its stores in South Africa (Gesellschaft für Internationale Zusammenarbeit, 2011). Another area of application is in the area of leisure and recreation where cold production equipment is used with CO_2 for skating (http://www.danfoss.com).

The use of CO_2 under transcritical cycle is also used in the food industry in the extraction of oils in bio-materials such as herbs, natural plants such as legumes, nuts and palms among others (Norhuda and Jussof, 2009). It is also used as a solvent for the processing of molten polymers, composites training and microcellular foam (Sameer, 2006). In the medical industry as a sterilizer in the transplantation of tissue (http://www.scientificamerican.com), as well as in the aeronautical industry for the cooling systems of rockets (Urbano *et al.,* 2009).

5. Conclusions

One of the main challenges when using CO_2 as a refrigerant is to obtain significant increments in the performance of transcritical systems in comparison with the conventional systems inasmuch as the performances are energetically insufficient, in reference to the refrigeration mode. As the investigation advances, without question, the use of CO_2 will be wider around the world, if there is no refrigerant in the market that can replace it as was done long ago with CFCs, of course.

The use of natural refrigerants like CO_2 is a practice that humankind should always do whereas this guarantees a low negative contribution to the environment. Still, an important part is the energy efficiency that the systems present and in this sense, the transcritical systems are not the best. For this reason, configurations that promote the increasing of the energy performance must be used.

CO_2 purposes are many and every day there are more of them. This is because this fluid is better positioned in the market day after day, and it is integrated into the range of strong options in refrigeration systems. One of the most latent applications is found without question in the area of automotive air-conditioning, in which, nowadays, there is no certainty about what refrigerant must be used. Given that, it is known that R-134a should be eliminated from automotive units in the years to come. Hence, it is here where we think there is an open area of opportunity for CO_2 to become the ideal fluid.

The disadvantages of handling this fluid must be also considered. However, currently, material science and facility safety have caused that the risk for high pressures pass the background, and because of this, the best is to continue with the investigation of upgrades, especially in the transcritical mode.

Considering that the tendency is the use of refrigerants with a low GWP, CO_2 looms as a good alternative to replace synthetic fluids, which main disadvantage is their great contribution to global warming.

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Received 15 October 2013; revised 2 April 2014

Investigation of fuel properties and engine analysis of Jatropha biodiesel of Kenyan origin

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Abstract
Biodiesel was produced from jatropha curcas oil of Kenyan origin through a two-step acid-base catalytic transesterification process. The relevant physicochemical properties of the produced biodiesel were tested according to appropriate standards and were found to be within the requirements. Engine tests were carried out in an Audi, 1.9 litre, turbocharged direct injection, compression ignition engine at different loads. Emissions were measured by a Horiba emission analyser system while combustion data was collected by a data acquisition system, from which, cylinder pressure and rate of heat release of the test engine in every crank angle were calculated. Though the biodiesel had slightly higher brake specific fuel consumption when compared to fossil diesel, its emission behaviour was significantly better. The combustion characteristics were also slightly higher as compared to fossil diesel. This study therefore concluded that biodiesel derived from jatropha curcas of Kenyan origin can be utilized as a safe substitute for mineral diesel.

Keywords: biodiesel, engine tests, fuel properties, jatropha

1. Introduction

1.1 General introduction

As petroleum prices continue to rise and concern for the environment grows, alternatives for diesel fuel becomes paramount. Scientists have invested considerable effort in searching for renewable substitutes of diesel fuel. Biodiesel, a mixture of mono alkyl esters of long chain fatty acids, is derived from renewable lipid feedstock, such as vegetable oil or animal fat. Biodiesel can be used in diesel engines without major modifications. It is becoming one of the fastest growing fuels in the global fuel market. It offers many advantages such as; it is renewable, energy efficient, nontoxic, sulphur free, biodegradable, allows cleaner combustion and reduces global warming gas emissions. Specifically, the combustion of biodiesel from vegetable oil does not add the net CO_2 to the atmosphere because the next crop will re-use the CO_2 to grow.

Biodiesel can be produced from both edible and non-edible plants, however, the major hindrances in widespread application of biodiesel from edible oils and fats are strains in food production, price and availability. On the other hand, non-edible biodiesel feedstocks are easily available in developing countries and are very economical compared to edible oils (Demirbas, 2008). Vegetable oils are important especially in the rural areas of developing countries like Kenya, where there is vast unutilized land in which edible crops cannot thrive and lack modern forms of energy.

1.2 Current status of biodiesel in Kenya

Very little research has been conducted on biodiesel production and tests from agricultural African countries like Kenya, which currently do not have any known commercial reserves for fossil fuels despite the government effort in exploring possible areas. Therefore, all liquid fuels are imported into the country, which is expensive and consume a big percentage of the country's foreign exchange.

Production and use of biodiesel in Kenya is still in its early stages and minimal research has been done in this sector despite the country's potential to produce this fuel. This is against the aims of Kenya to use biodiesel as a substitute for conventional diesel and other fossil fuel sources as well as for export by the year 2020 (Mogaka et al., 2010). Very few researchers have done an in-depth analysis of biodiesel produced from Kenyan feedstocks. These feedstocks include croton megalocarpus (Aliyu et al., 2011, Aliyu et al., 2010) and yellow oleander (Keriko, 2007). Other researchers only characterized the oils e.g. moringa oleifera (Tsaknis. et al., 1999), Calodendrum capense, Croton megalocarpus, jatropha curcas and Cocos nucifera (Wagutu et al., 2009), while others just mentioned castor oil, croton megalocarpus, jatropha curcas and grain amaranthus as other oils in Kenya but without any practical analysis (Keriko, 2007).

1.3 Aim of study

It is a known fact that the type of biodiesel produced from vegetable oil depends on the type of vegetable oil and its geographical location. For instance, several researchers found that jatropha oil produces superior biodiesel compared to many other non-edible feedstocks (Makkar and Becker, 2009, Treese *et al*., 2010, Pramanik, 2003) and biodiesel of different origins differs in properties and characteristics as indicated in the research of Emil *et al.,* (2010), Lu *et al.,* (2009) and Foidl *et al.,* (1996) (Jatropha seed oil), and Lalas and Tsaknis (2002) (moringa oleifera oil).

The current research deals with the production, analysis and characterization of biodiesel from Kenyan Jatropha curcas oil. Short term combustion characteristics, engine performance and emission analysis of this biodiesel was also performed to evaluate its behaviour in an engine. Jatropha curcas, which produces a non-edible vegetable oil, is a large shrub or small tree of the family *Euphorbiaceae*. In Kenya, it is naturalized in bush lands and along rivers in western, central and coastal parts of the country at altitudes of 0-1650 meters above sea level (Tomomatsu and Swallow, 2007). So far, no study has reported an in-depth analysis (in terms of fuel characterization and full engine tests) of biodiesel produced from jatropha oils of Kenyan origin.

2. Materials and equipment

2.1 Material used

Jatropha curcas oil was supplied from the Kitui region, Kenya. The chemicals used were analytical reagents; potassium hydroxide and methanol, at 85% and 99.5% purity respectively, and were sourced from local suppliers. The Free Fatty Acids (FFA) were determined by using the simple titration method as per literature (Knothe *et al.,* 2005).

2.2 Biodiesel production and property measurements

The transesterification process was preferred for biodiesel production in this study, where the experiments were conducted using beakers as reactors. The reaction beaker was placed on a thermostatically controlled heating plate equipped with a magnetic stirrer. The heating plate had a maximum heating capacity of 420 °C and a maximum agitation of 2000 rpm. A thermometer, held by a retort stand was immersed in the beaker to verify the temperature of the reaction mixture. Fuel properties of the samples were tested according to the standards recorded in Table 1.

The free fatty acid content of jatropha oil in this study was initially found to be 5.6%. An acid esterification process followed by the transesterification method was then used to prepare the jatropha curcas methyl esters (JCME). The acid pre-treatment process was intended to convert the free fatty acid to esters using an acid catalyst (H_2SO_4) to reduce the free fatty acid concentration of the oil to below 1%. The acid catalyst (w/w of oil: 0.5% H_2SO_4) and 6:1 methanol/oil molar ratio was used and the mixture stirred at 500 rpm for 1 hour at 50 °C, then after settling, the pre-treated oil was collected and purified (Ramadhas *et al.,* 2005a).

After acid esterification, the transesterification was carried out at the following standard conditions: 6:1 methanol/oil molar ratio (mol/mol), 1.0 wt% potassium hydroxide, 55-60 °C reaction temperature, 400 rpm agitation speed and 60 minutes reaction time (Rashid *et al*., 2008). After the reaction and settling, the biodiesel (methyl esters) was collected and purified from all impurities. The final product, that is, the biodiesel, formed as a clear, light yellow liquid.

Table 1: Methods for determination of fuel properties

Property	Units	Test method
Cetane number	-	ASTM D613
Heating value	MJ/kg	ASTM D240
Density	kg/m^3	ASTM D941
Viscosity	mm^2/s	ASTM D445
Flash point	°C	ASTM D93-94
Water content	%	ISO 12937
Acid value	mg KOH/g	ASTM D974
Cloud point	°C	ASTM D2500
Lubricity	μm	ISO 12156
Oxidation stability	h	EN 14112

The fatty acid composition of biodiesel was analysed using a gas chromatography mass spectroscopy (Agilent 6890N) coupled to an inert mass-selective detector (Agilent 5973). The percentage composition of the individual components was obtained from electronic integration measurements using flame ionization detection. All relative percentages determined by GC for each fatty acid sample are the mean of three runs.

2.3 Engine tests equipment

An Audi, 1.9 L, turbocharged direct injection (TDI) compression ignition (CI) engine (Figure 3) was used in this experiment. It is a four-stroke, four-cylinder, water cooled diesel engine. Table 2 records the engine's technical specifications.

Table 2: Experimental engine details

Engine model	Audi, 1.9 L, TDI
Capacity	1896 cm^3
Bore	79.5 mm
Stroke	95.5 mm
Compression ratio	19.5:1
Maximum power	66 kW, at 4000 rpm
Maximum torque	202 Nm, at 1900 rpm
Fuel system	Direct injection with electronic distributer pump

Figure 1 depicts the equipment connections for the engine test. The engine (1) was coupled with a dynamometer (2) to provide brake load, while the engine throttling and dynamometer settings were controlled by a computer (9). A pressure transducer (10) was installed in one of the piston cylinders. Cylinder pressure signals from pressure transducer were amplified by a charge amplifier (12), and connected to the SMETech COMBI-PC indication system (8) for data acquisition. The data acquisition system was externally triggered 1024 times in one revolution by an incremental crank angle transducer-optical encoder (11). Fuel was introduced from a fuel tank (3) equipped with flow measurement system. During fuel switching, the fuel tank was drained from the engine fuel filter, new fuel was introduced into the tank until the fuel filter was full, and the engine was then started and allowed to run for a few minutes to clear fuel lines and stabilize.

Emission was measured by Horiba emission analyser system (5) equipped with analyser modules NDIR (AIA-23), H.FID (FIA-22), and H.CLDC (CLA-53M) for measuring (CO, CO_2, and HC), (THC), and (NO_x) respectively and a smoke meter (6) connected before the oxidative converter at the engine exhaust pipe (4). The system was connected to the computer (7), and emission data recorded.

2.3 Heat release calculations

During the engine test, the engine was run at constant speed, 3000 rpm, at different loads, from a low idle to 100% load at intervals of 25% of full load. Heat release was subsequently calculated from cylinder pressure and crank angle readings, and emission data was then collected. The net heat release is calculated by a computer program using equation 1 from pressure data (collected with respect to the crank angle) and cylinder geometry with respect to the crank angle. The analysis was derived from the first law of thermodynamics for an open system which is quasi static (Ren *et al*., 2008):

$$\frac{dQ_n}{d\theta} = \frac{1}{\gamma - 1}\left(\gamma p \frac{dV}{d\theta} + V\frac{dp}{d\theta}\right) \quad (1)$$

Where:

$\frac{dQ_n}{d\theta}$ = Net heat-release rate (J/Degree crank angle).

γ = The ratio of specific heats, $\frac{c_p}{c_v}$

V and $\frac{dV}{d\theta}$ terms are calculated as shown in equation 2 and equation 3 respectively.

$$V = V_c + A \times r\left[1 - \cos\left(\frac{\pi\theta}{180}\right) + \frac{1}{\lambda}\left\{1 - \sqrt{1 - \lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}\right\}\right] \quad (2)$$

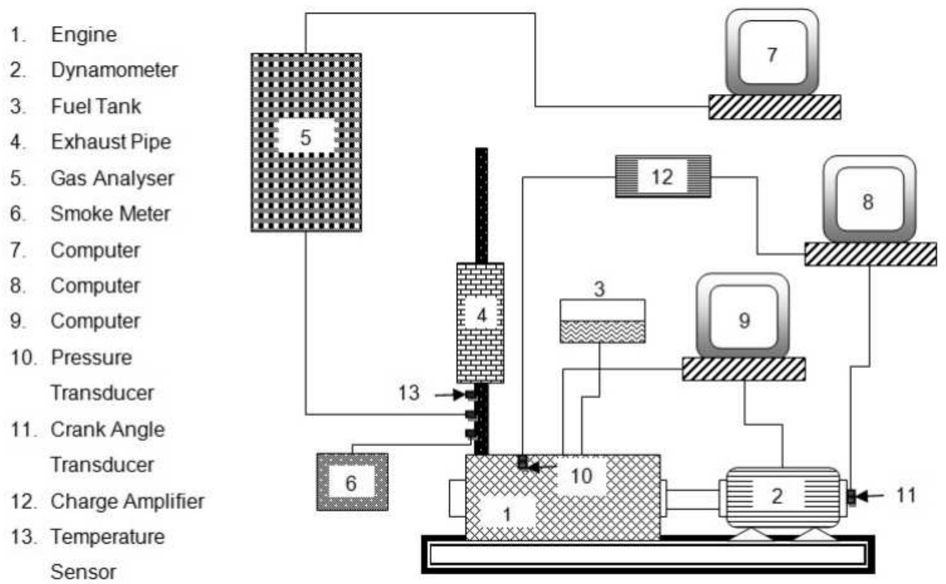

Figure 1: Engine test experimental set up

And

$$\frac{dV}{d\theta} = \frac{\pi\theta}{180} \times r \left[\sin\frac{\pi\theta}{180} + \frac{\lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}{2 \times \sqrt{1-\lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}} \right] \quad (3)$$

But: $\lambda = \frac{1}{r}$ and $A = \frac{\pi}{4} D^2$

Where:
- l = Connecting rod length.
- r = Crank radius.
- D = Cylinder bore.
- V_c = Clearance volume.

3. Results and discussion

3.1 Biodiesel composition

The fatty acid profiles are the major indicators of the properties of any biodiesel. In this work, biodiesel from jatropha curcas (JCME) had a fatty acid composition as depicted in Table 3. The composition of the fatty acids affects various properties of biodiesel, such as oxidation stability, low temperature flow properties and lubricity.

Table 3: Fatty acid composition of JCME

Fatty acid composition (wt. %)	*JCME*
Palmitic methyl ester (C16/0)	15.3
Palmitoleic methyl ester (C16/1)	1.1
Stearic methyl ester (C18:0)	6.4
Oleic methyl ester (C18/1)	40.1
Linoleic methyl ester (C18/2)	36.9
Linolenic methyl ester (C18/3)	0.2
Saturated fatty acids methyl esters (SFA)	21.7
Monounsaturated fatty acids methyl esters	41.2
Polyunsaturated fatty acids methyl esters	37.1

3.2 Biodiesel properties

Table 4 summarizes the properties of methyl esters from the oil. The properties of fossil diesel are included for comparison purposes. These properties indicate the suitability of methyl esters in this study as an alternative fuel for diesel engines. Properties of the methyl ester from the oil were found to be within the limits of biodiesel standards (ASTM D6751 and EN 14214).

3.3 Brake specific fuel consumption

Figure 2 illustrates the brake specific fuel consumption (BSFC) of the fuel samples tested with respect to different loads. It is defined as the fuel consumption rate divided by its corresponding engine power output. It can be observed that BSFC decreases as the load increases for all fuel samples. This could be caused by the increased air pressure at higher loads; the air pressure in the intake manifold increases as the load increases owing to the increased power of the turbocharger (high exhaust gas volume, flow and temperature) hence the reduced amount of fuel per unit power produced. From the results, it was observed that pure diesel fuel (D2) had the lowest BSFC, approximately 10% lower than that of jatropha curcas methyl ester (JCME) at full load. The higher BSFC of JCME and jatropha curcas oil (JCO) means that more fuel was consumed and less power was produced. This was expected because of the lower heating value (HV) of JCME and JCO compared to D2, at the same time, their higher density also contributed to higher BSFC. At zero load, JCME and JCO had lower BSFC probably because intrinsic oxygen contained in the fuels improved combustion at no load.

3.4 Exhaust gas temperature

Figure 3 depicts the variation of exhaust gas temperature (EGT) versus loads for test fuels. The EGT increases with increasing load. The EGT of JCO was lower than that of JCME (except at zero load). The EGT of JCME was in turn lower compared to

Table 4: Fuel properties of biodiesel, diesel and biodiesel standards

Property	*Units*	*JCME*	*Diesel*	*ASTM D6751*	*EN 14214*
Density @ 15 °C	Kg/m^3	855	832	-	860-900
Viscosity @ 40 °C	mm^2/s	4.43	3.01	1.9-6.0	3.5-5.0
Acid value	mgKOH/g	0.09	-	0.8 maximum	0.5 maximum
Flash point	°C	186	-	130 minimum	101 minimum
Heating value	MJ/kg	37.82	42.63	-	-
Lubricity	μm	218	-	-	-
Cetane number	-	56.54	54.60	47 minimum	-
Cloud point	°C	1	-16	-	-
Pour point	°C	-3	-19	-	-
Water content	ppm	460	50	500 maximum	500 maximum
Sulphur content	ppm	0.0025	45		
Oxidation stability at 110 °C	h	9.65	-	-	6 minimum

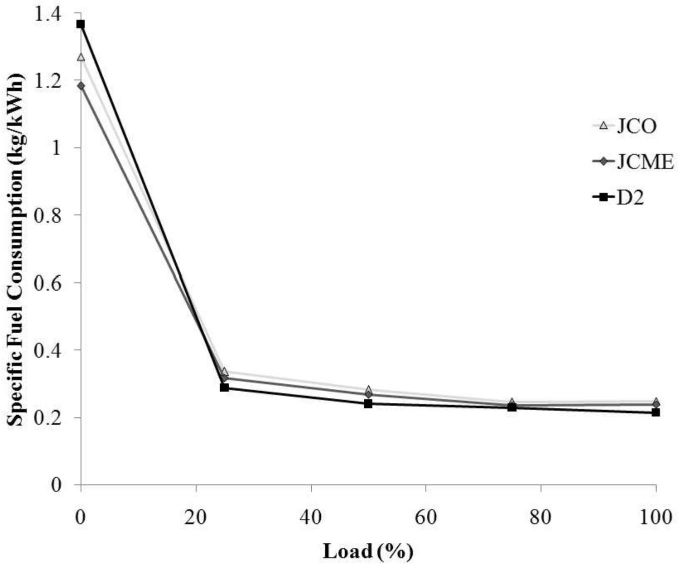

Figure 2: BSFC for different fuel samples at different loads

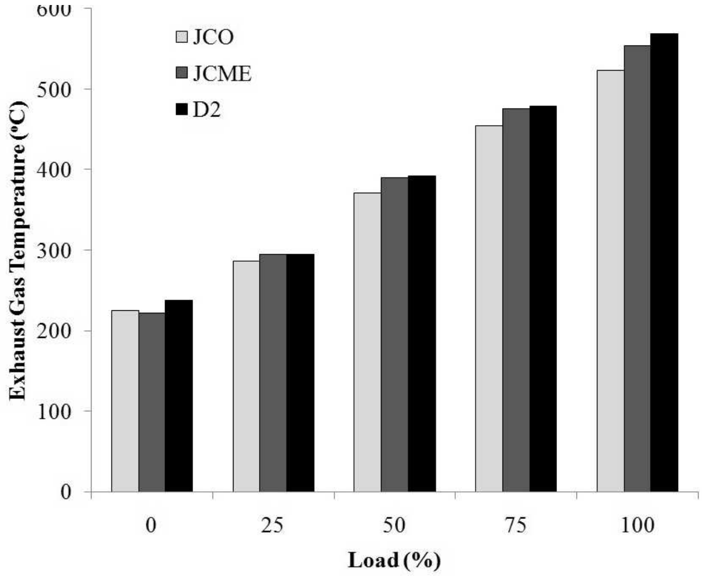

Figure 3: EGT for different fuel samples at different loads

that of D2. This might be attributed to the heating value of the fuels. The higher the heating value, the higher the exhaust temperature and vice versa.

3.5 Elements present in fuels (C, H, and O)

Figure 4 depicts the major elements carbon, hydrogen and oxygen (C, H and O) contained in fuel samples. It can be observed from the figure that C is the most dominant element in the fuel samples, with the minimum amount being observed in JCME. The amount of H contained is fairly similar for all samples, with JCME recording the highest content. D2 fuel contains the highest C, while JCME and JCO have similar O content. Oxygen is an important element in combustion in that its content influences the stoichiometric air-fuel ratio during the combustion process. A correct amount of inbound oxygen in a fuel contributes to its better combustion. A high cetane number and presence of intrinsic oxygen in the fuel could result in emission reduction because more complete combustion will consume more of the ignitable mixture formed in the combustion chamber; hence carbon monoxide and hydrocarbon emissions will be reduced.

3.6 Emissions

Engine emissions which were experimentally obtained are plotted against load as further described.

3.6.1 Oxides of nitrogen (NO_x)

Figure 5 depicts the oxides of nitrogen (NO_x) emissions of different fuel samples tested at different load conditions. In general, the formation of NO_x is affected by the peak flame temperature, the high burning gas temperature, the ignition delay and the content of nitrogen and oxygen available in the reaction mixture (Heywood, 1998). It was observed that as the load increases, the in-cylinder temperature also increases and thus higher absolute NO_x (ppm) formation results.

Higher cylinder pressure could contribute to increased NO_x emissions, due to the increased peak combustion temperature at higher engine loads. The results conform to those in the literature (Purushothaman and Nagarajan, 2009b; Purushothaman and Nagarajan, 2009a). D2 exhibited slightly higher NOx emissions compared to JCME, especially at lower engine loads, however, JCO had the highest overall emission of NO_x. The possible reason for this may be the slow burning of the more viscous biodiesel, due to the residence time of the fuel in the high temperature zone being higher. Moreover, the NO_x emission increase can be associated with the oxygen content in the fuel samples

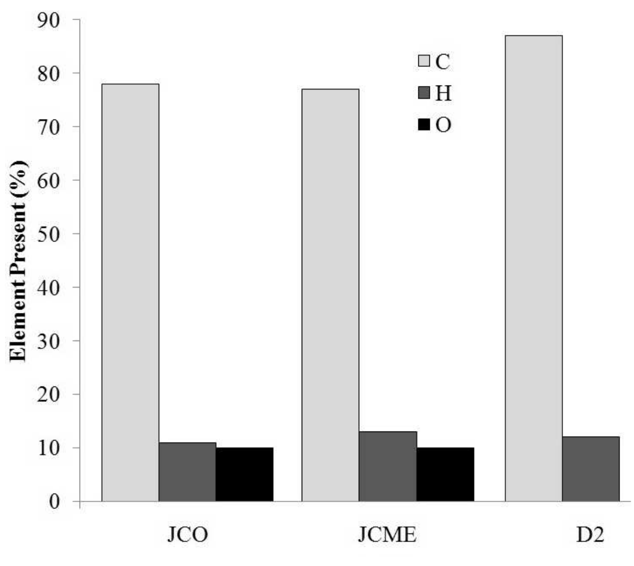

Figure 4: Contents of elements (C, H, and O) in fuel samples

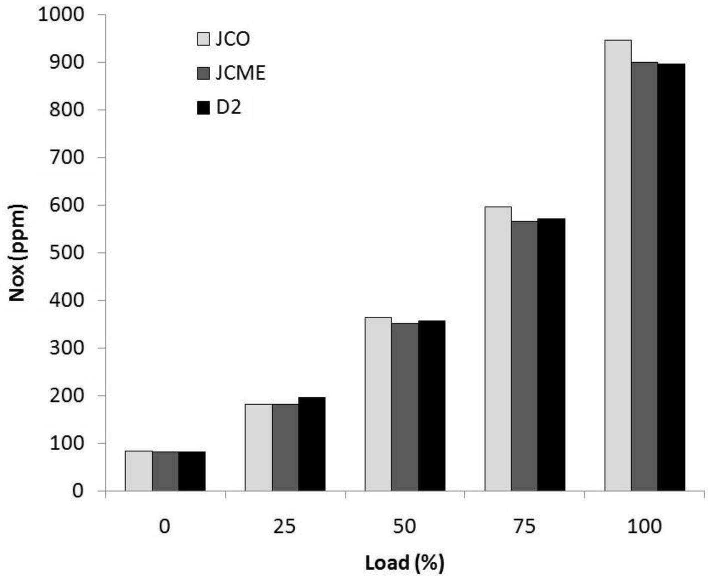

Figure 5: NOx emissions for different fuel samples at different loads

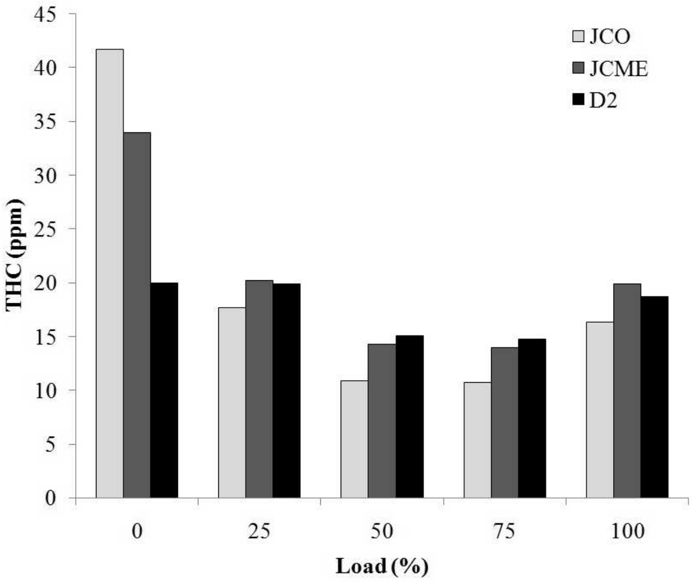

Figure 6: THC emissions for different fuel samples at different loads

since the fuel with oxygen may provide additional oxygen for the formation of NO_x (Ramadhas *et al.,* 2005b).

3.6.2 Total hydrocarbons (THC)

The variation of THC emissions with loads is shown in Figure 6. It can be observed that THC emissions are maximum on idling, whereas lower THC values are obtained at 50% and 75% loads at steady engine speed. A similar trend was also observed in the literature, whereas high THC emission is observed at lower loads and maximum loads (Shi *et al.*, 2006). The small difference of D2 and JCME samples in THC emission could possibly be attributed to the higher fuel supply for a given load which produces slower combustion times and counteracts the possible benefit of the presence of fuel borne oxygen in enhancing the combustion process of JCME (Aliyu *et al.*, 2011; Banapurmath *et al.*, 2008).

3.6.3 Carbon monoxide (CO)

The formation of CO with increasing load is illustrated in Figure 7. The figure shows that CO emission decreases with engine load. High CO emissions were observed at lower loads, with the lowest emissions recorded at 75% engine load. CO is a product of incomplete combustion; thus at higher engine loads, the higher combustion temperature promotes more complete combustion hence fewer CO emissions. The results of these CO emissions agree with those reported in the literature (Purushothaman and Nagarajan, 2009a; Banapurmath *et al.,* 2008). The relatively poor atomization and lower volatility of fuel samples is responsible for this trend. In addition, at lower loads, CO emissions are increased due to incomplete combustion, whereas at 100% load CO emissions are slightly increased compared to 75% load, due to the local presence of a richer mixture in the combustion chamber (Cheng *et al.,* 2008).

3.6.4 Carbon dioxide (CO_2)

Fuel derived from vegetable oils reduces overall carbon dioxide in the atmosphere when it is used to run diesel engines, since plants absorb carbon dioxide during growth (Demirbas, 2008; Balat and Balat, 2008). Figure 8 illustrates CO_2 emission results. It can be observed that CO_2 emission increases as the load increases at the same engine speed. It can also be observed that JCO had the least CO_2 emissions followed by JCME then D2 in higher loads. Oxygen present in vegetable oils and biodiesel supports combustion hence, will lead to more CO_2 emissions at low loads due to complete combustion. This fact has been observed from literature (Mbarawa, 2008) as diesel exhibits lower CO_2 emissions. At higher loads, however, poor fuel atomization and lower combustion duration override the advantages of added oxygen in JCO and JCME and thus, incomplete combustion results.

3.6.5 Smoke

Smoke emissions results are shown in Figure 9. Diesel fuel recorded higher smoke emissions at all loads. Maximum smoke emission values were observed at 100% load for both fuels, where D2 fuel indicates the maximum value, while JCO recorded the minimum value under the same load condition. The presence of oxygen in JCO and JCME samples could explain their lower emission values (Chen et al., 2008, Purushothaman and Nagarajan, 2009b).

3.7 Combustion analysis

The variation in injection timing exerts a major influence on the engine performance and exhaust emissions. To understand and optimize the combustion process, a careful analysis of cylinder pressure and heat release has been performed, which furnishes precise information about the combustion process when using biodiesel. For this purpose, the experiments were carried out in a TDI compression ignition in order to analyse the combustion characteristics of the fuel samples tested.

3.7.1 Cylinder pressure

Figure 10 indicates the peak cylinder pressure for different fuels at different engine load conditions. Figure 11 illustrates the variations of cylinder pressure with crank angle degree (CAD) for the fuels at full load conditions and constant engine speed of 3000 rpm. Similar graphs were obtained at other loads with differences only in the magnitude of pressure and the corresponding crank angle in which it appears. In a CI engine, the cylinder pressure depends on the burned fuel fraction during the premixed burning phase, that is, the initial stage of combustion. Cylinder pressure characterizes the ability of the fuel to mix well with air and burn. High peak pressure and maximum rate of pressure rise correspond to the large amount of fuel burned in the premixed combustion stage (Agarwal, 2007).

It can be noted that JCO produced the least peak cylinder pressure, while JCME produced the highest at all loads. All fuels exhibited peak cylinder pressures between crank angles of -10 °C and 10 °C, with lower load levels exhibiting peak cylinder pressure in negative crank angles and vice versa. It was also observed that the cylinder pressure increases as the load increases. This increase in pressure is to be expected in a TDI diesel engine. It is caused by the increased amount of injected fuel and charge pressure in the air intake manifold at higher loads. The temperature and volume flow of the exhaust gases that pass through the turbo charger influence the characteristics of air flow in the intake manifold, owing to the increased spinning speed of the turbocharger turbine and the heat exchange between exhaust gas and the charged air. The amount of air forced into the intake manifold increases as the load increases, since the high temperature, high velocity exhaust gas that passes through the turbocharger turbine causes a rise in the velocity of intake air, which forces more air into the cylinders. The increased amount of air causes larger amounts of fuel to be injected into the cylinder, which in turn, causes higher cylinder pressure.

JCME produced the highest peak pressures probably because of increase in ignition delay when using it. This ignition delay increases the amount of fuel burned within the premixed burning phase, causing high values of peak pressure and rate of pressure rise. JCME's lower viscosity (compared to JCO) and its contribution of intrinsic oxygen (com-

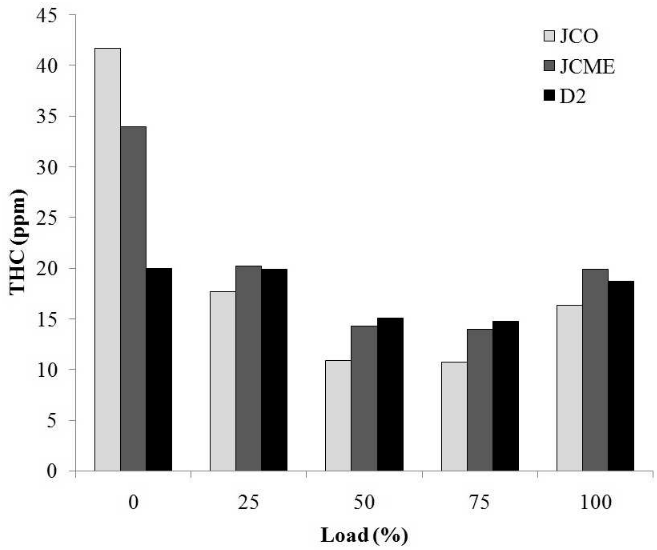

Figure 7: CO emissions for different fuel samples at different loads

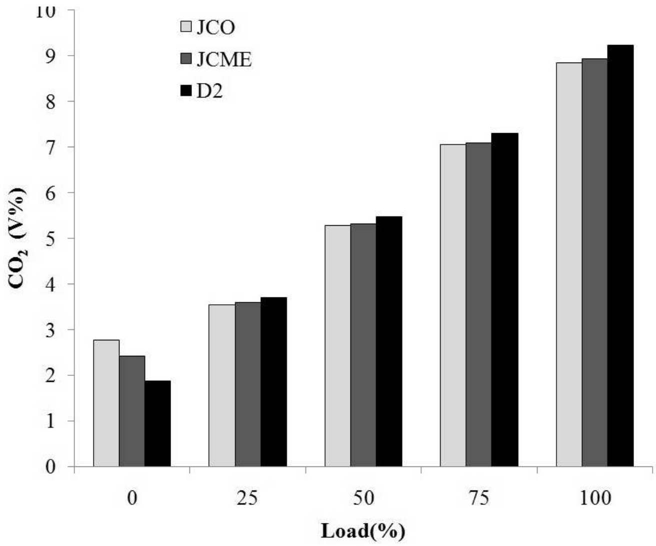

Figure 8: Carbon dioxide emission at different load conditions

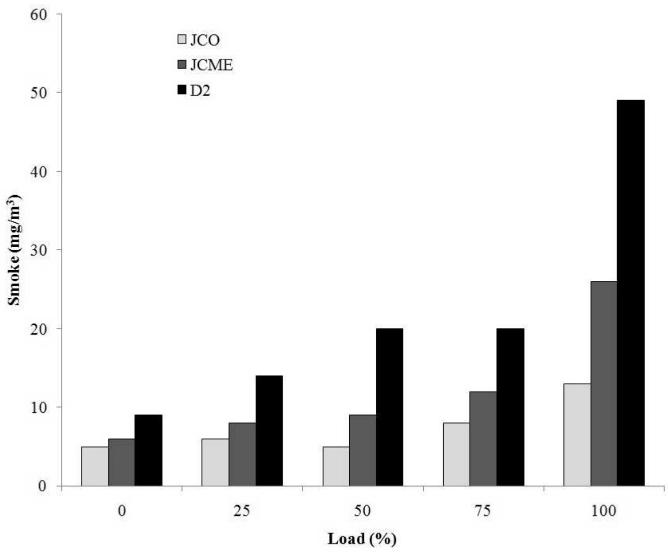

Figure 9: Smoke emissions for different fuel samples at different loads

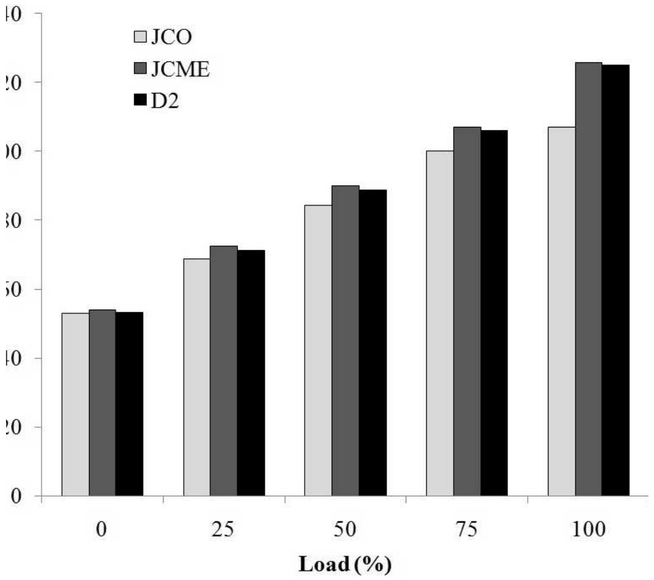

Figure 10: Peak cylinder pressure at different engine loads

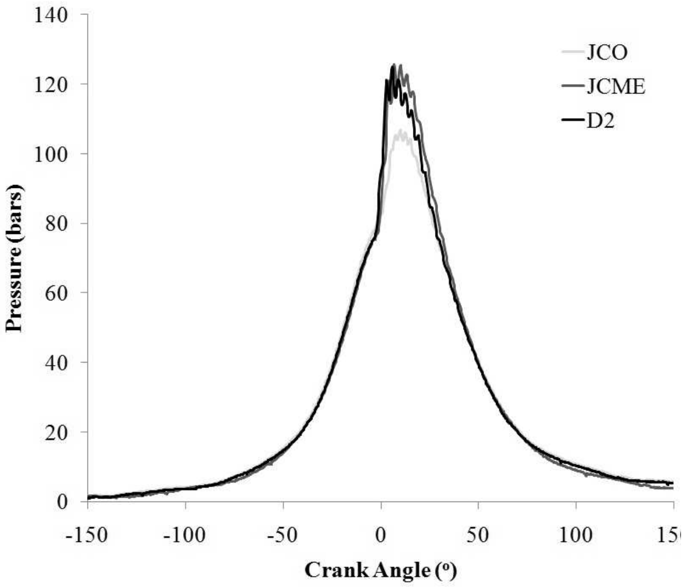

Figure 11: Cylinder pressure variation with crank angle at full load

pared to D2) may also be the reason for high cylinder pressure. High viscosity of JCO is the reason for its lower peak cylinder pressure, as the fuel spraying is affected by viscosity. Complete combustion depends to a large extent on fuel-air mixing. More complete combustion influences high cylinder pressure (Purushothaman and Nagarajan, 2009b; Purushothaman and Nagarajan, 2009a). Diesel (D2) indicates a slightly lower peak cylinder pressure than JCME, which may also be caused by oxygen-fuel mixing, which is more efficient in fuel that contains intrinsic oxygen (Agarwal, 2007; Ramadhas *et al.*, 2005b).

3.7.2 Heat release

Figure 12 depicts peak heat release rates for different fuels. Figure 13 illustrates the variations of heat release with crank angle degree (CAD) for the fuels at full load conditions and constant engine speed of 3000 rpm. Similar graphs were obtained at other loads with differences only in the magnitude of heat release and the corresponding crank angle in which it appears.

All fuels follow a similar trend i.e. the peak heat release values increase as the load increases. This may be caused by high temperature and high cylinder pressure, better fuel-air mixing, and higher flame velocity associated with higher loads. All fuels experience rapid premixed burning followed by diffusion combustion, as is typical for naturally aspirated engines. After the ignition delay period, the premixed fuel air mixture burns rapidly, releasing

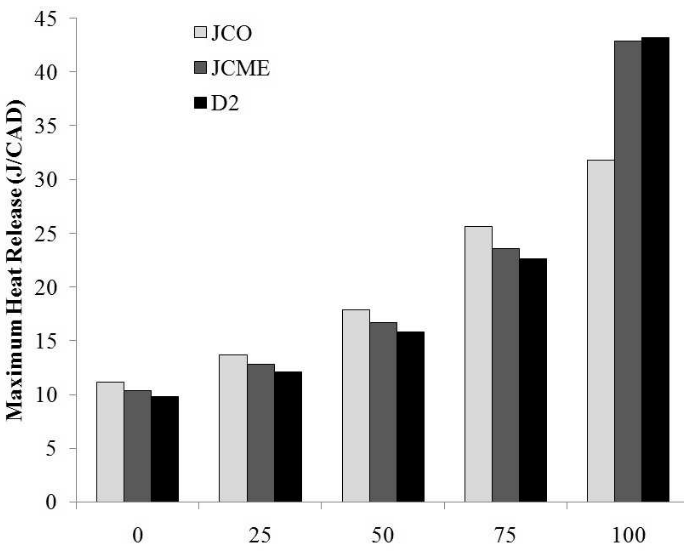

Figure 12: Maximum rate of heat release at different engine loads

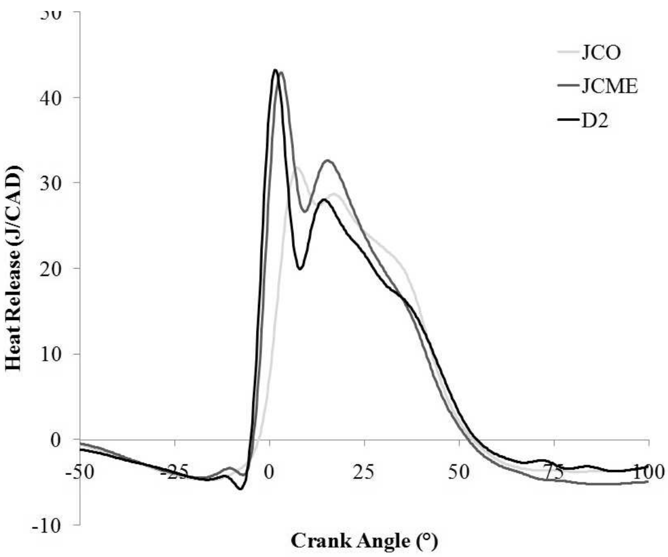

Figure 13: Heat release variation with crank angle at full load

heat at a very rapid rate, after which diffusion combustion takes place, where the burning rate is controlled by the availability of the combustible fuel-air mixture. It can be seen that JCO and JCME recorded an improvement in the heat release rate at the premixed combustion period. The presence of oxygen in these fuels decreased their cetane number and increased the ignition delay period. Therefore, while the engine was running with biodiesel, increased accumulation of fuel during the relatively longer delay period resulted in a higher rate of heat release. Even though D2 fuel exhibits high HV and lower viscosity, the intrinsic oxygen property of the other fuels influenced the heat release results observed. Because of the shorter delay period of diesel, its maximum heat release rate occurs earlier in comparison with JCME, while JCO was the last to exhibit its maximum heat release.

3.8 A summary of key findings

- The properties of methyl esters obtained using optimal parameters conformed to biodiesel standards (ASTM 6751and EN 14214).
- The engine test results indicated that BSFC output from JCO and JCME were slightly weaker than those of mineral diesel; this is possibly due to their lower heating value compared to mineral diesel.
- The CO_2 and smoke emissions from mineral diesel were generally higher than JCME and JCO emissions. As for THC and CO emissions, it was affected by loading, where at lower loads, JCO had the highest emissions and at higher loads, D2 lead. NO_x emissions were approximately the same for all fuels except in full load where JCO exhibited slightly higher emissions.
- Peak cylinder pressure and maximum heat release for all fuels increased with loadings where JCME exhibited the highest values in nearly all loads. The peak pressure and maximum heat were occurring at a range of crank angle between -10° and 10°. JCO had the least peak cylinder pressure whereas D2 had the least maximum heat release in nearly all loadings.

4. Conclusion

The foregoing analysis of fuel properties, engine performance, emissions characteristics, and combustion characteristics suggests that JCME can indeed be used as a fuel in diesel engines, resulting in reduced emissions and improved fuel properties and engine performance as compared to D2 fuel.

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Received 3 May 2012; revised 10 March 2014

A 2MW direct drive wind turbine; vector control and direct torque control techniques comparison

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Abstract
This paper presents a comparative study on the most popular control strategies used to control high power, Direct Drive Wind Turbines. The studied wind turbine is equipped with a supervision scheme in order to fulfil Grid connection requirements (GCR). For the generator-side converter, performances of the Field Oriented Control (FOC) and Direct Torque Control (DTC) are compared. Concerning the grid-side converter, Voltage Oriented Control (VOC) and Direct Power Control (DPC) are examined. The comparison is based on various criteria mainly, steady-state and transient performances. In addition, performances are evaluated in terms of low voltage ride through capabilities (LVRT), power limitation and reactive power control. It has been shown that best power quality features are given by vector control techniques. On the other hand, direct control offers the better dynamic response and power cross-coupling is substantially lower. Furthermore, during fault, the wind turbine does not trip for both techniques. However, vector control is better since it gives low power oscillations .

Keywords: Direct Drive, FOC, DTC, VOC, DPC, supervisory control

1. Introduction

Wind energy is a promising alternative to traditional energy sources (The European Wind Energy Association, 2010). Due to increasing wind power penetration, the improvement of control strategies becomes a major challenge for manufacturers in order to comply with the grid connection requirements (Gabriele, 2008). Consequently, new wind power plants are increasingly expected to provide ancillary services which maintain reliable operation of the interconnected transmission systems (Lov *et al.,* 2007; Heier, 2006). Compared to other wind turbine technologies (Muni Prakash *et al*., 2012; Pena *et al.,* 1996), Direct Drive topology showed itself to be the most promising technique because it offers variable speed operation and fulfils GCR with high efficiency (Akhmatov, 2005).

The power electronics subsystem is composed of two voltage source inverters (VSI) separately controlled. Control strategies based on direct power and vector oriented control are investigated for normal and distorted operating conditions. Control techniques for the Permanent Magnets Synchronous Generator intend to control the torque and the flux. On the other hand, control strategies for the GSC intend to decouple the active and reactive power delivered to the grid. To achieve these objectives, vector control techniques require current control, in the rotating reference frame, and decoupling between the components so that the electromagnetic torque and power are indirectly controlled. In direct control strategies, the first step is to estimate torque and power. These two variables are then controlled directly, resulting in less complex and faster algorithms (Bin Wu *et al.,* 2011).

For both techniques the advanced controller part was not considered. However, they give very good control performance, but the performance study was not explored for a large wind farm connected to grid (Lather *et al.,* 2013).

Consequently, it is relevant to evaluate the performance of vector and direct control techniques, in order to identify which is the most suitable large scale generation. Therefore, in this work, FOC and DTC control strategies for the generator-side converter and VOC and DPC for the grid-side converter are considered.

In the first section, the wind turbine model is presented. The second section presents the control strategies of the generator-side convertor. Performances of the two control techniques are simulated and analysed. The third section presents the control strategies of the GSC with a comparative study. Finally, in the last section presents the developed supervision algorithm used to control reactive power. Transient stability of the wind system during grid faults are investigated for both control strategies.

2. Direct drive wind turbine model

The wind turbine consists of the following components: A three-bladed rotor with the corresponding pitch angle controller; the MPPT algorithm; a PMSG with two back-to-back power converters (Carlsson, 1998), a DC-Link capacitor, and a grid LC-filter. The control of the PMSG-WT consists of two parts, the generator side control and the grid side control. The scheme of the wind turbine system is shown in Figure 1.

3. Control strategies for the generator side converter

3.1 Field oriented control

FOC strategy is generally applied to the Generator-side converter (Figure 2). It allows controlling the rotor speed through the control of the electromagnetic torque. Torque control is achieved by setting to zero the d component of current and the torque is controlled through the q component. Details of this control strategy for variable pitch wind turbine and the MPPT algorithm are presented in Allagui et al., (2013).

3.2 Direct torque control

The basic principle of DTC is to select proper voltage vectors using a pre-defined switching table (Rahman *et al.,* 2003). Selection is based on hysteresis control of stator flux linkage and the torque. In which case, the stator flux and the torque are controlled independently and directly. The torque hysteresis comparator is a three valued comparator. Whereas that, the flux hysteresis comparator is a two valued comparator. The control scheme of DTC is developed as shown in Figure 3.

3.3 Comparative study of DTC and FOC control

In order to compare the dynamic behaviour of these control techniques, FOC and DTC responses are presented in Figure 4. Simulations have shown that the FOC has higher torque ripple than DTC technique. Electromagnetic torque oscillation is evaluated using the Total Waveform Oscillation (Two), given by:

$$Two = \frac{\sqrt{T_{em-rms}^2 - T_{em-dc}^2}}{\left|T_{em-dc}\right|} * 100\% \quad (1)$$

Where $T_{em\text{-}rms}$ and $T_{em\text{-}dc}$ stand for the electromagnetic torque rms and average values, respectively.

Steady-state simulations show that the best power quality features and the smaller power-tracking error are given by the VOC technique. On the

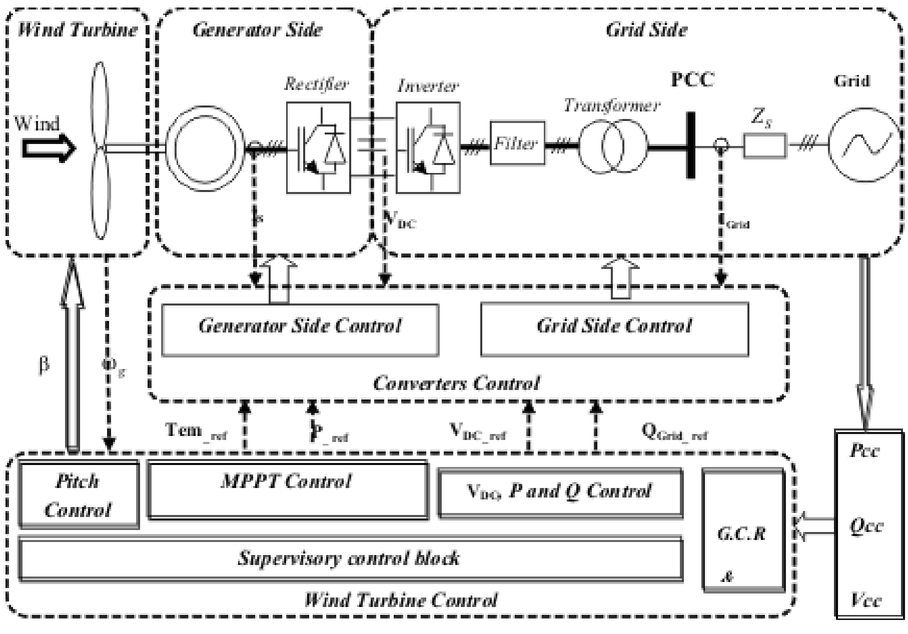

Figure 1: General control scheme of PMSG-WT

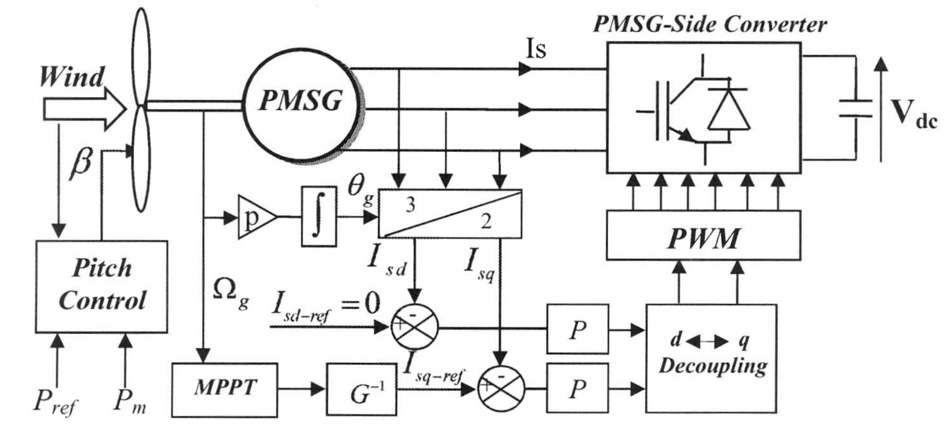

Figure 2: Block diagram of the field oriented control

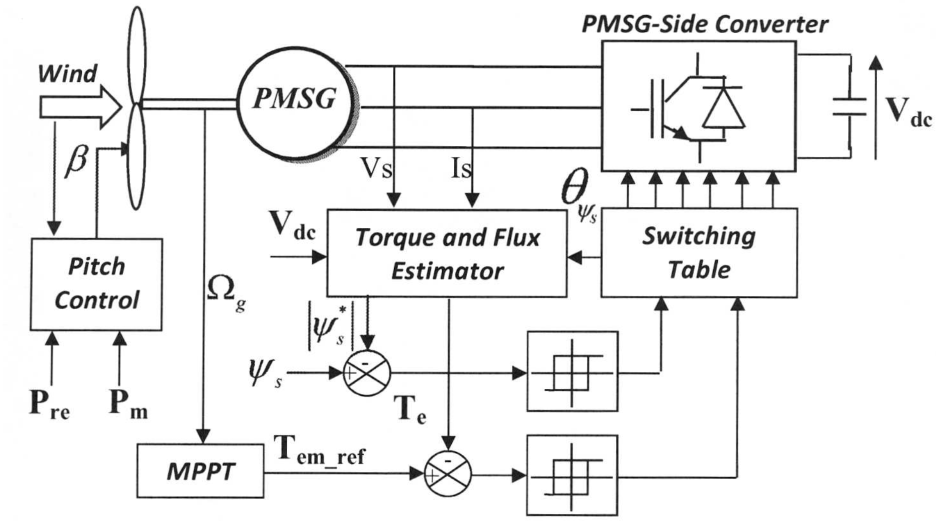

Figure 3: Block diagram of the direct torque control

other hand, DTC technique offers the fastest transient behaviour without overshoot (~9%). Table 1 shows a brief description of simulation results along with the characteristics of each control strategies.

Table.1: Control features and requirements for FOC and DTC control

Features	FOC	DTC
Switching Frequency	Constant f = 2 kHz	Constant f = 5 kHz
Modulation Technique	PWM	Hysteresis
Current THD	4.6%	11.2%
Tracking Error	0.83%	6.79%
Torque TWO	1.34%	1.03%
Cross-coupling Effect	Yes	No
Dynamic performance	Setting time (<112 ms)	Setting time (<82ms)
	Rise time (<22 ms)	Rise time (<17 ms)
	Overshoot (~24%)	Overshoot (~9%)

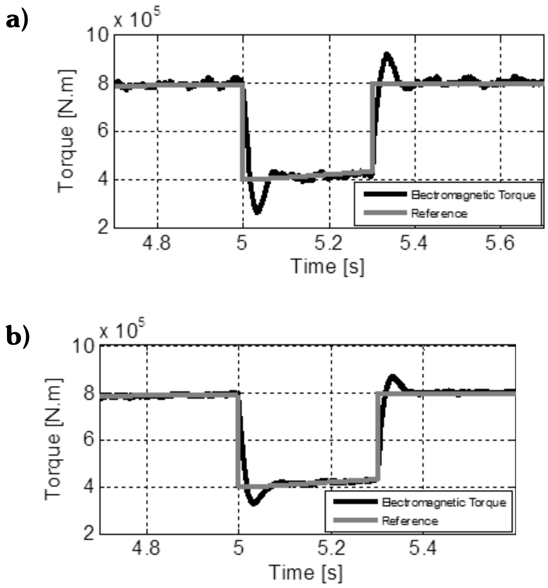

Figure 4: Simulation results versus the time-domain waveforms of the PMSG electromagnetic torque, during a load transient: a) FOC technique; b) DTC technique

4. Grid side converter control strategies

4.1 Voltage oriented control (VOC)

The grid side converter is mainly used to control active and reactive powers delivered to the grid, in order to keep the DC Link voltage constant, and to ensure the quality of the injected power. Voltage Oriented Control requires internal current control loops in the rotating dq frame and the elimination of the current cross coupling between the d and q components (Belhadj *et al.,* 2006; Woo Kim *et al.,* 2010). The connection to the grid is achieved through an LCL filter and a transformer. The Phased Locked Loop (PLL) gives an estimation of , the angle of the grid voltage. In this way, an accurate synchronization between the inverter voltage and the voltage at the Point Common Coupling (PCC) is obtained. The PLL technique is detailed in Allagui *et al.,* (2013). The control of the DC-link voltage, active and reactive power delivered to the grid, and grid synchronization are shown in Figure 5.

4.2 Direct power control (DPC)

Conventional direct power control allows to directly controlling active and reactive powers using a switching table. It uses the same principle of DTC. Conventional DPC is characterized by the high ripple in grid currents which gives a poor power quality (Escobar *et al.,* 2003). In addition, the switching frequency is not controlled, which increase the difficulty for correct harmonic filter design. Consequently, conventional DPC is combined with SVM technique to obtain constant switching frequency and low current distortion (Malinowski *et al.,* 2004). The developed DPC for the grid-side converter is shown in Figure 6. In this figure, the unity power factor is obtained by setting the reactive power reference to zero.

4.3 Comparative study of DPC and VOC control

The steady-state is evaluated by means of current THD measurements, active and reactive power

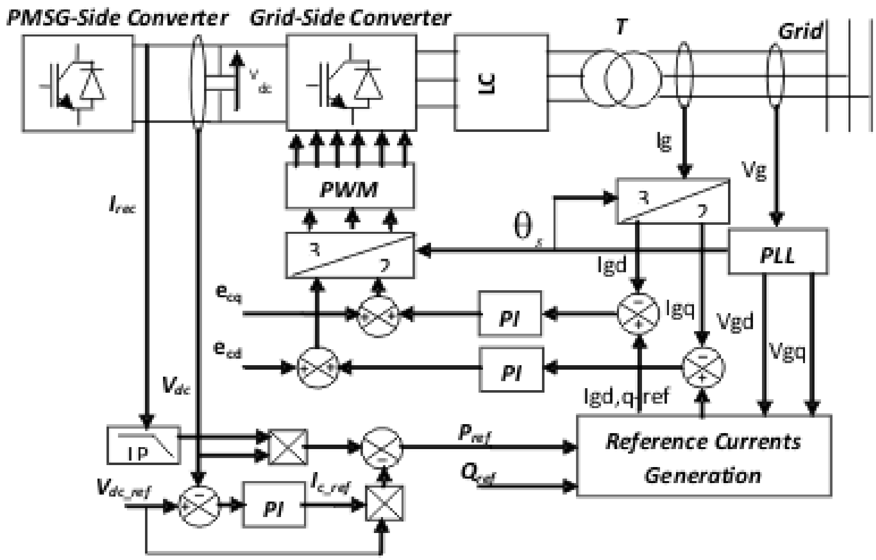

Figure 5: Block diagram of the voltage oriented control technique

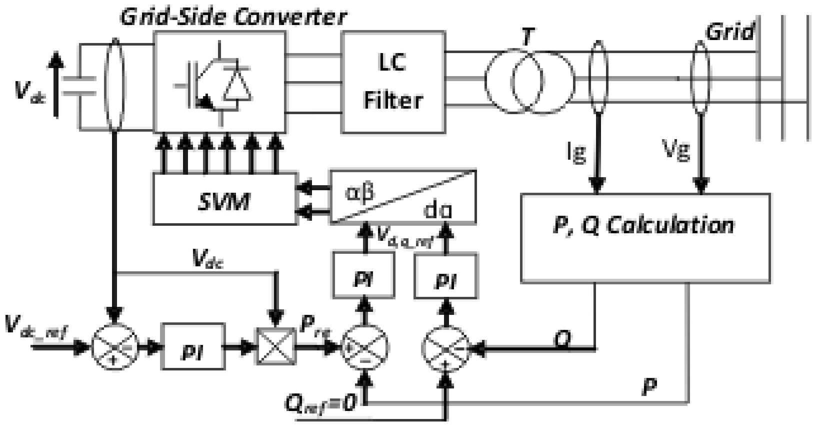

Figure 6: Block diagram of the direct power control technique

ripple values (ΔP, ΔQ) and some DC-link performance features as the voltage ripple ΔV_{DC}. On the other hand, the cross-coupling effect and the typical dynamic performance criterions as the settling time, rise time and overshoot are considered in the transient-state operation.

4.3.1 Steady-state performance
Figures 7 and 8 show the grid currents, spectrum analysis and power performance for the grid side converter, using both the VOC-type control strategy and the DPC techniques. As can be observed, the VOC control shows the best power quality (THD = 2.3%) and the minimum power ripple (ΔP = 8%, ΔQ = 9.2%). The DPC control leads to a dispersed harmonic spectrum with a large THD of around 9% with considerable power ripple values (ΔP = 17.6%, ΔQ = 19.4%).

According to the IEEE standards 519-1992 recommendation, the limit of harmonic distortions for distributed power systems connected to the grid should not exceed 5% (IEEE 519 Working Group, 1992). In this way, only VOC meets the grid connection requirements (GCR). On the other hand, the VOC strategy shows a small tracking error of around 0.32%, while the absolute tracking error reaches 4% in the DPC case. Furthermore, the voltage ripple in the DC-link capacitor is clearly smaller in the VOC (ΔV_{DC} = 5%) than the DPC strategy (ΔV_{DC} = 14%) (), see Figure 9.

4.3.2 Transient performances
Several simulations have been carried out in order to verify the behaviour of the proposed control algorithms during transients operation. These simulations involve the grid side converter configura-

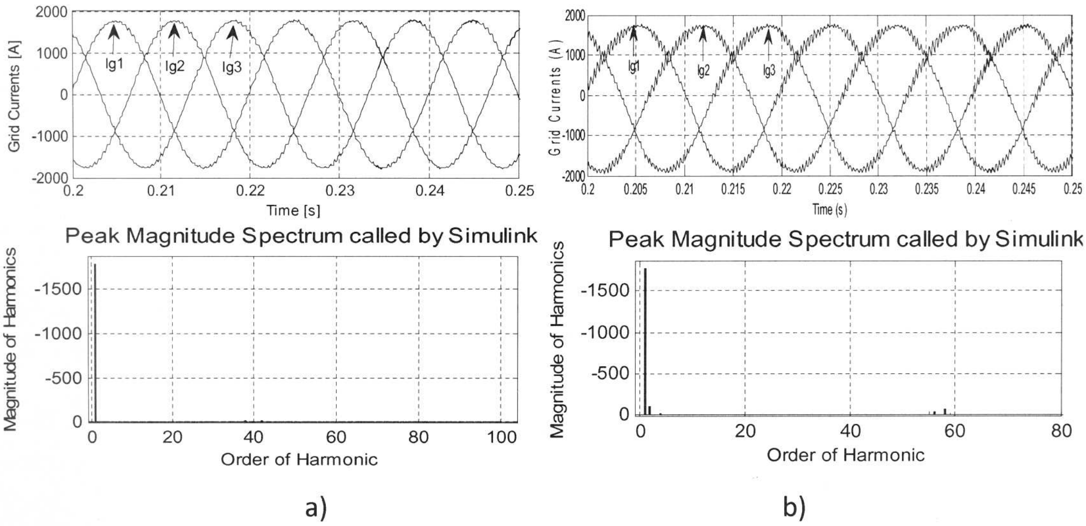

Figure 7: Grid currents and their spectrum analysis: a) VOC techniques b) DPC techniques

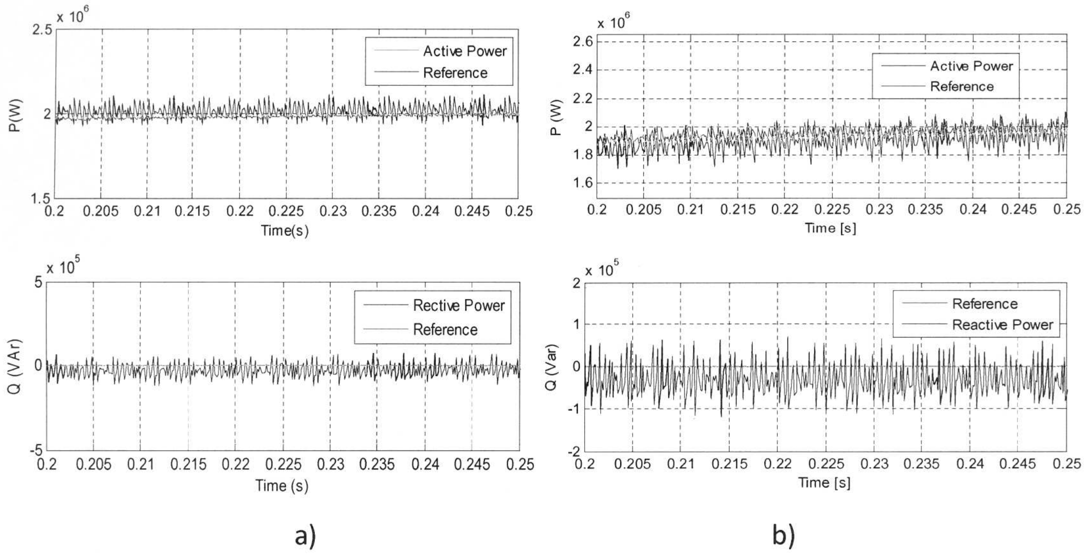

Figure 8: Active and reactive power behaviours: a) VOC techniques b) DPC techniques

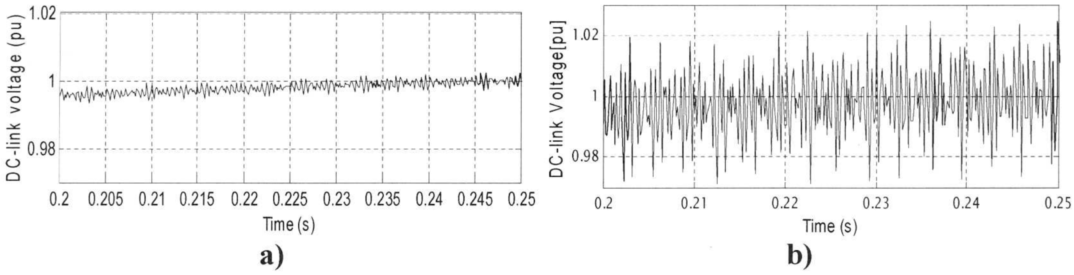

Figure 9: DC-link voltage: a) VOC techniques b) DPC techniques

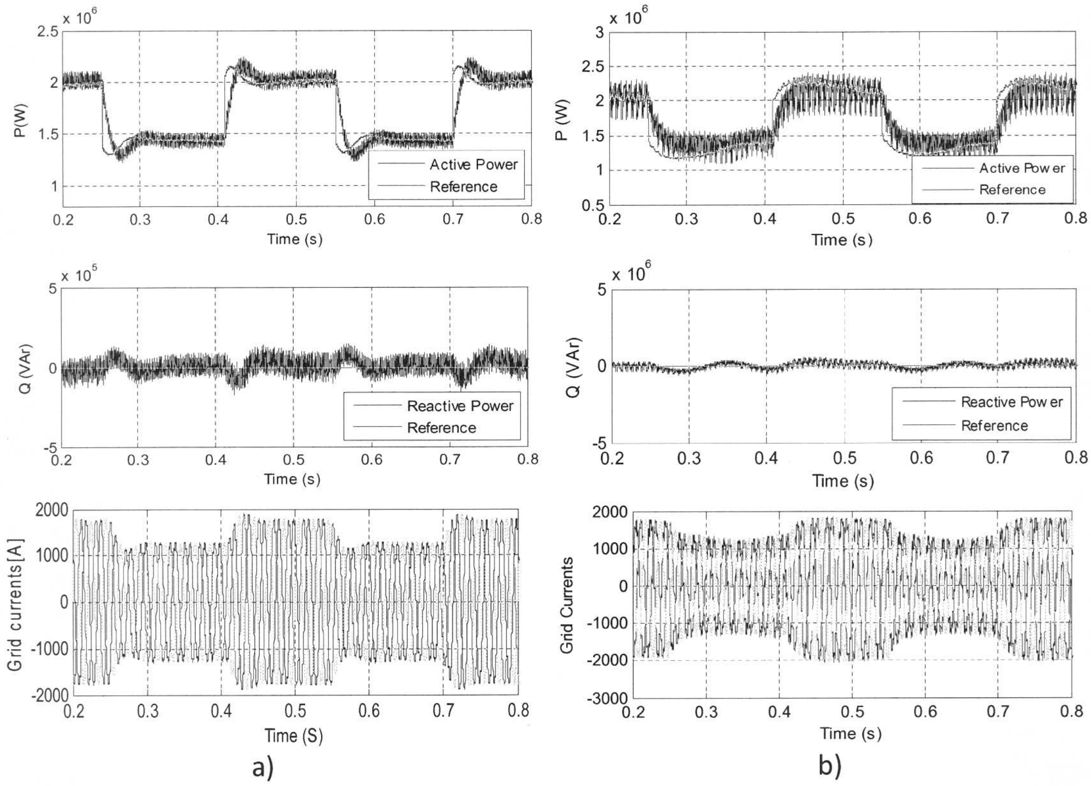

Figure 10: Instantaneous response during active and reactive power reference steps: a) VOC techniques b) DPC techniques

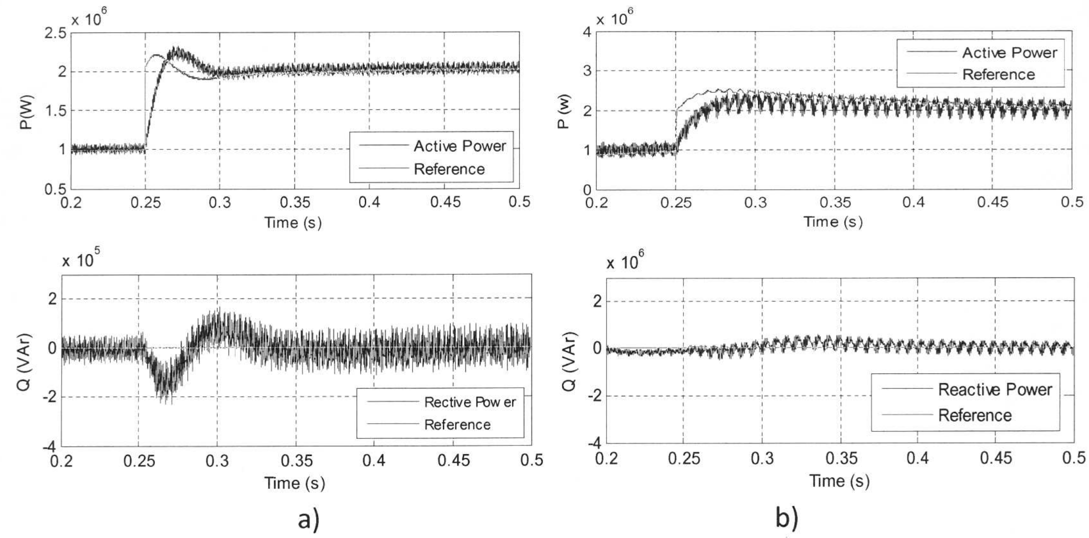

Figure 11: Active and reactive power transient behaviours: a) VOC techniques b) DPC techniques

tions with the VOC and DPC-based control strategies. Active-power reference steps from 1.4MW to 2MW have been applied (30% of nominal power). Note that reactive power steps will produce similar results in transients, so these cases are not evaluated. Figure 10 shows the instantaneous active and reactive power behaviour during active reference steps. As shown, the DPC technique is clearly faster than the VOC techniques in the power tracking task. The transient performance shows the expected behaviour in the VOC-based strategy (Figure 11).

To quantify the transient behaviour, a power band near 5% of the rated power is established. In this way, a setting time close to 60.6ms, a rise time below 17.2ms and a small overshoot of around 25% can be observed in the VOC-based configuration. Yet, the DPC needs a setting time below 44.8ms, with a rise time of around 13ms without overshoot (~5%) in power tracking requirements. Furthermore, there is no cross-coupling effect between active and reactive power in the DPC, whereas the VOC shows a substantial perturbation in the reactive power behaviour when active power changes are applied.

The steady-state simulations show the best power quality features and the smaller power-tracking error is obtained with VOC techniques. On the other hand, DPC -based strategies offer the fastest transient behaviour without overshoot and cross-coupling effect. Table 2 shows a brief description of the simulation results along with the characteristics and requirements of each control strategy. Consequently, it is concluded that combination of vector and direct control represents the best choice, depending on the desired performance trade-off.

Table 2: Control features and requirements for VOC and DPC techniques

Features	*VOC*	*DPC*
Switching Frequency	f = 2 kHz Constant	f = 5 kHz Mean value
Modulation Technique	PWM	SVM
Current THD	2.3%	8.77%
Tracking Error	0.32%	4%
Power ripple	ΔP (8%) ΔQ (9.2%)	ΔP (17.6%) ΔQ (19.4%)
DC-link Ripple	ΔV_{DC} (5%)	ΔV_{DC} (14%)
Cross-coupling Effect	Yes	No
Dynamic Performance	Setting time (<60.6ms)	Setting time (<44.8ms)
	Rise time (<17.2ms)	Rise time (<13.3ms)
	Overshoot (~25%)	Overshoot (~5%)

5. Reactive power control supervisory

5.1 Low voltage ride through (LVRT) capabilities and voltage grid support

Currently, wind turbines should stay connected to the grid in the case of voltage dips (Lather *et al.*, 2013). This is of particular importance to the TSOs, since wind farms disconnection could cause major loss of power generation and consequently, power system instability (Lov *et al.*, 2007; E.ON Netz GmbH, 2006). Grid connection requirements used in this paper are those defined by the TSO E.ON Netz and are presented in Figure 12 (Lov *et al.*, 2007). According to these requirements, wind farms should remain connected to the grid following voltage sag with a 100% magnitude during a minimal period of 150 ms. The Figure shows the limit above which turbines should not trip.

The purpose of the supervisory reactive power control presented in this section is to regulate the voltage at the specified PCC (Figure 13). To achieve this target, the Grid side converter must supply reactive current equivalent to 2% In per 1% Un voltage dip. Thus, the supervisory control block contains two control levels which are activated according to the dip magnitude:

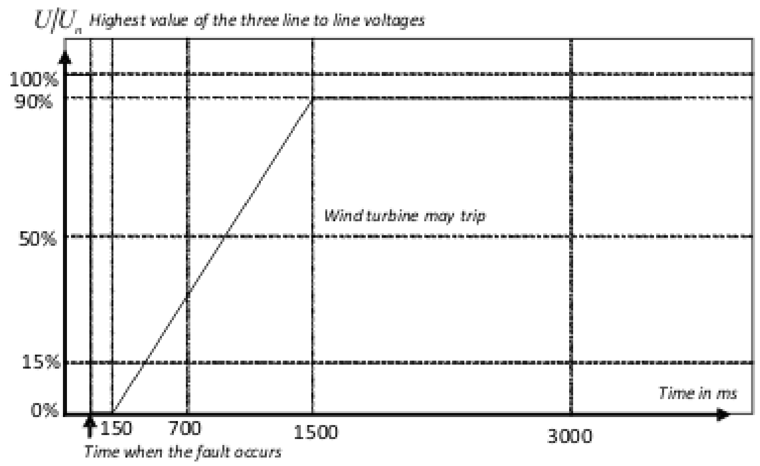

Figure 12: Voltage profile according to the requirements of LVRT capability through Lov *et al.*, (2007)

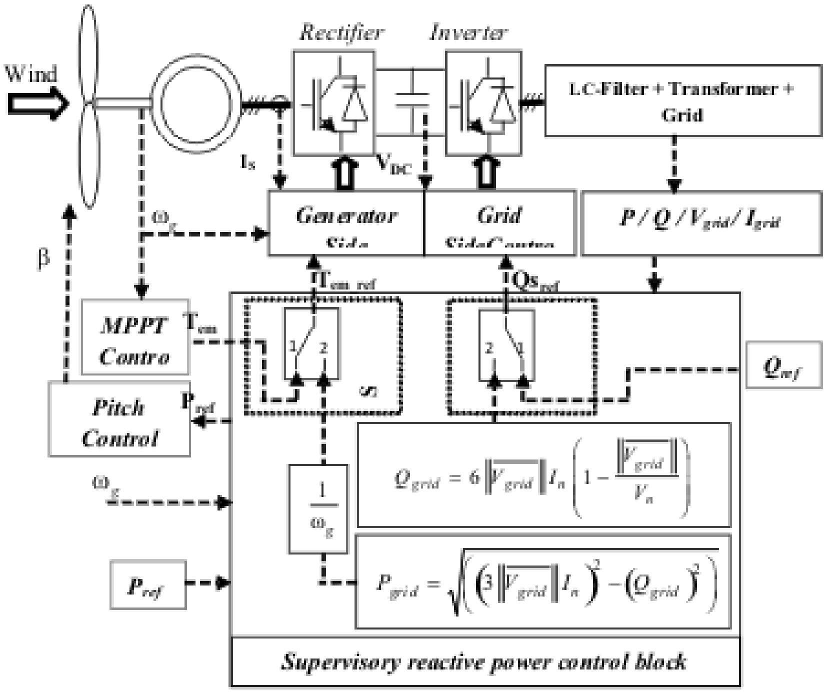

Figure 13: Schematic diagram of the reactive power supervisory

- *Level 1:* $\left\|\overline{V_{grid}}\right\| \geq 50\% V_n$:

  In this condition, the normal operating mode is activated. The torque reference T_{em_ref} is given by the MPPT algorithm and power production is optimized. Reactive power reference is fixed by the TSOs.
- *Level 2:* $\left\|\overline{V_{grid}}\right\| \leq 50\% V_n$:

  During faults, the wind turbine should supply reactive currents to the grid. In addition, grid currents should not exceed nominal ratings of power semiconductors. Therefore, reactive power reference Q_{grid} is calculated by:

$$Q_{grid} = 6\left\|\overline{V_{grid}}\right\| I_n \left(1 - \frac{\left\|\overline{V_{grid}}\right\|}{V_n}\right) \qquad (2)$$

Then, Q_{grid} is used to calculate active power reference P_{grid} given by (3):

$$P_{grid} = \sqrt{\left(\left(3\left\|\overline{V_{grid}}\right\| I_n\right)^2 - \left(Q_{grid}\right)^2\right)} \qquad (3)$$

The calculated power P_{grid} should be available at the output of the generator side converter. Therefore, when a voltage dip is detected, torque reference switches to another value given by (4):

$$T_{em-ref} = \frac{P_{grid}}{\omega_g} \qquad (4)$$

5.2 Comparative study of DPC and VOC control

Figure 14 and 15 show the response of the control strategy to a symmetrical voltage dip. The dip magnitude is divided in two part; 45% then 70% of the rated voltage, as illustrated in Figure 15.

This result shows that DC-link voltage remains stable during the fault and the over-voltage does not exceed 10% of the rated value. For both control techniques; the wind turbine remains connected to the grid and supports the voltage by delivering reactive power, the grid currents are limited to the nominal value. After the fault, the active power is increased to the initial value with a gradient higher than 20% of the rated power per second, as required by the GCR. It is noticed that rotor speed is no longer controlled during the fault since torque reference is not taken from the MPPT algorithm. Finally, vector control technique (VOC) is characterized by a lower harmonic distortion THD and higher efficiency. On the other hand, DTC is less computational demanding and it gives a better dynamic response.

6. Conclusion

The synthesis and analysis of two different control strategies for PMSG-WT have been carried out. The results of this comparative study show that both control strategies can be used to control direct drive wind turbines. However, the best power quality features and the smaller power-tracking error are obtained with vector control techniques. On the other hand, direct control offers the better dynamic response without overshoot and cross-coupling effect.

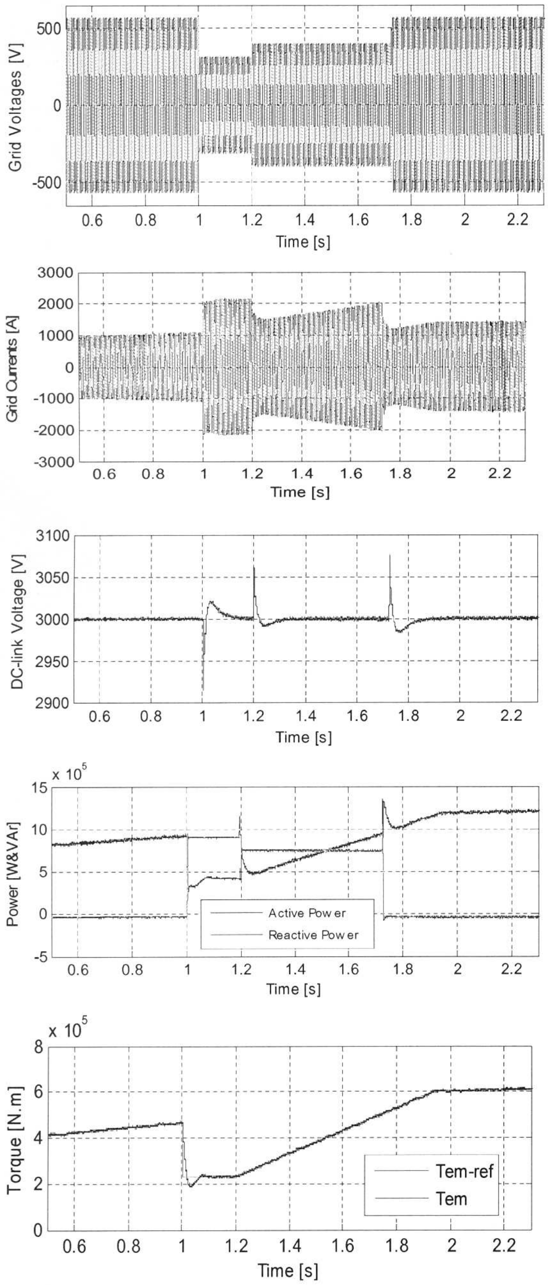

Figure 14: Wind turbine behaviour during a asymmetrical fault (type A), with the VOC techniques

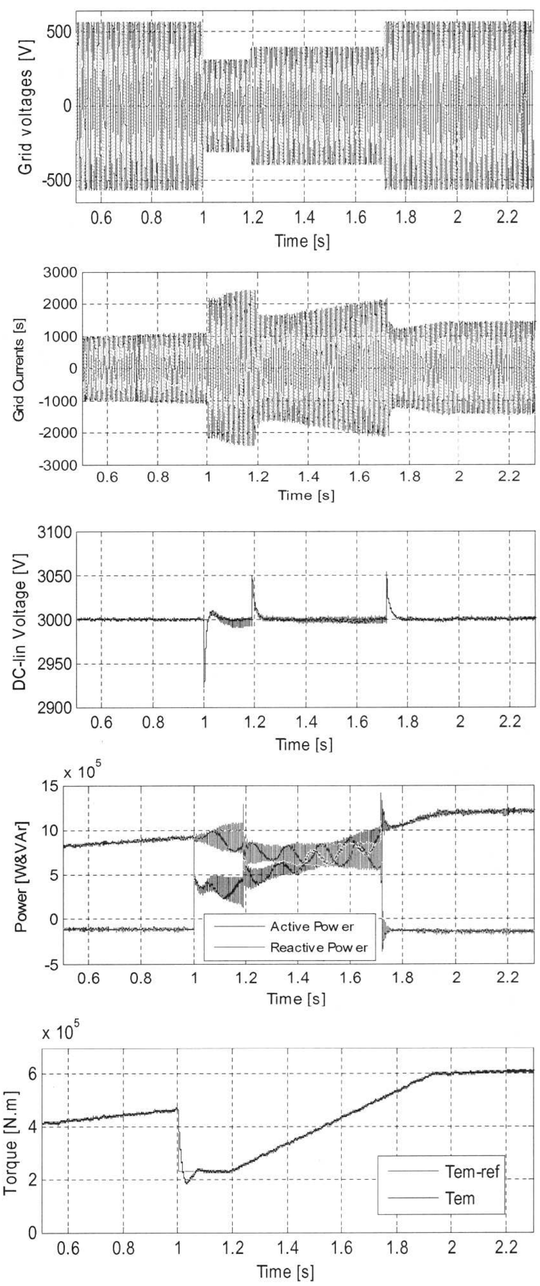

Figure 15: Wind turbine behaviour during symmetrical fault (type A), with the DPC techniques

According to the simulation results, the wind turbine does not trip during a grid fault. In addition it delivers reactive power to support the grid voltage. Thus, supervisor performances are in accordance with the GCR for both control strategies. We conclude that the vector control is better as adapted, and the responses with the direct control are faster.

Appendix: See overleaf

Acknowledgment
This work was supported by the Tunisian Ministry of High Education, Research and Technology.

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Received 3 November 2013; revised 16 May 2014

Appendix: Wind turbine, PMSG side and grid side parameters

Wind Turbine Parameters
$P = 2MW$
$N_m = 24rpm$
$J_{tot} = 6.2.10^6 \, kg.m^2$
$D = 75m$
3 Blades
Variable Speed
Collective Pitch

PMSG side parameters
$P_{nom} = 2.02MW$
$U_{nom} = 1.75kV$
$I_s = 660A$
$r_s = 32 \, m\Omega$
$L_{sd} = 2.7mH$
$L_{sq} = 1.7mH$
$\phi_v = 18.6wb$
$p = 32$

Grid side parameters
$S = 2MW$
$U_{dc} = 3kV$
$C_{dc} = 20mF$
$R_g = 0.3 \, m\Omega$
$L_g = 0.01mH$
$C_f = 35\mu F$

Erratum

In Volume 25 No 1, the paper titled 'An indicative assessment of investment opportunities in the African electricity sector', by C Taliotis et al., was published on pages 2-12. On Page 4, Table 1 has been revised regarding the 100% efficiencies and 100% availabilities.

With regard to *100% efficiencies*, this is simply the way any renewable technology is modelled in MESSAGE. It does not refer in any way as to how efficient the technology is in transforming solar irradiation or wind into electricity. This is common practice for all renewable technologies that do not have fuel input. To explain further, in MESSAGE the modeller has to define an input and output ratio (i.e. efficiency). When it comes to renewable technologies one has 2 options:

a) Define an additional fuel (e.g. sunlight, wind etc) to act as an input (100%) and then add an out-

Table 1: Power plant parameters used in the model
Miketa and Merven (2013b)

Plant type	*Investment cost ($/kW)*	*Fixed O&M ($/kW)**	*Variable O&M ($/MWh)*	*Efficiency*†	*Life (yrs)*	*Capacity factor*	*Availability*†
Diesel centralized	1070	0	17	35%	25	80%	90%
Diesel 100 kW system							
(industry)	659	0	55	35%	20	80%	90%
Diesel/Gasoline 1kW system (residential/ commercial)	692	0	33	35%	10	80%	90%
HFO	1350	0	15	35%	25	80%	90%
OCGT	603	0	20	30%	25	85%	93%
CCGT	1069	0	3	48%	30	85%	93%
CCGT Associated Gas	1069	0	3	48%	30	85%	93%
Supercritical coal	2403	0	14	37%	40	85%	94%
Nuclear	5028	93	1.37	33%	60	92%	93%

Renewables	*Investment cost ($/kW)*	*Fixed O&M ($/kW)**	*Variable O&M ($/MWh)*	*Efficiency*	*Life (yrs)*	*Capacity factor*	*Availability*
Hydro (run of river)	1282	21	1.14	N/A	50	54-80%	67-80%
Hydro (dam)	2718	21	1.14	N/A	50	60-100%	90-100%
Small Hydro	4000	0	5	N/A	50	50%	N/A
Biomass	2500	0	20	38%	30	50%	93%
Bulk Wind (30% CF)	2000	0	16	N/A	25	30%	90%
Bulk Wind (40% CF)	2000	0	14	N/A	25	40%	85%
Solar PV (utility)	2000	0	20	N/A	25	25%	N/A
Solar PV (rooftop)	2100	0	24	N/A	25	20%	N/A
Solar PV rooftop (1 hr storage)	4258	0	24	N/A	25	22.5%	N/A
Solar PV rooftop (2 hr storage)	6275	0	24	N/A	25	25%	N/A
Solar thermal without storage	3000	0	22	N/A	25	35%	N/A
Solar thermal with Storage	5400	0	19	N/A	25	50%	N/A
Solar thermal with gas co-firing	1388	0	19	53%	25	85%	93%
Geothermal (cheap)	3500	30	1.03	N/A	25	85%	N/A
Geothermal (expensive)	4500	0	1.03	N/A	25	85%	N/A

** Fixed O&M costs have been incorporated within Variable O&M costs for the majority of technologies.*

† Efficiencies and availabilities of renewable energy technologies indicated as 'N/A' have been taken into consideration when calculating the generation potential of the respective resource.

put to define the efficiency (e.g. 48% for wind).

b) Have no input and define output as 100%. If this option is chosen one has to account for the ability of the technology in question to convert sunlight/wind etc. into power outside the model. In our case, this was done when calculating the potentials for RE in the publication cited as Hermann *et al,* 2012.

The second option has the advantage of a smaller matrix being generated by the model and thus a faster calculation, and therefore we chose this. Thus, 'efficiency' as mentioned in the paper is simply the input-output ratio of each technology as defined in the actual model. It should have been made clearer in the paper.

Similarly, with regard to *100% availabilities*, one has to take into account the capacity factor at the same time. The total amount of time that the technology is available is a function of the multiplication of these two values. Furthermore, these two values are dependent on the load-curve defined for the technology (i.e. its availability/output during each time-slice of the year). In MESSAGE, availability (defined as "operation time" in the model) refers to the share of time the technology is available each year, whereas plant factor (capacity factor) is taken into consideration in regards to each individual time-slice (e.g. day, night etc.). Furthermore, in our model, for instance, load-curves were added to solar technologies to include the daily variability in generation of these technologies. In essence, these technologies are completely blocked in certain time-slices (e.g. night) or are only allowed to provide a certain volume of power, in the case of storage options. These load-curves have not been included in the paper, but they exist in the model. Therefore, *by defining load-curves in MESSAGE, both the availability and capacity factor of a technology are considered*. These load-curves have not been included in the paper, as it would greatly increase the size of the annexes.

All in all, it was a mistake to quote both these values in the paper without a more detailed explanation.

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Prof Derick de Jongh entered academia after a 13-year banking career where he focused largely on human resource development, ultimately with a specialisation in corporate strategy, strategic market positioning and corporate citizenship.

His move to academia was spurred by a deep and personal realisation that the private sector in South Africa was failing dismally in reflecting critically on the purpose of business and, more specifically, on the role of business in society. His desire to understand this complex landscape better led him to enrol for doctoral studies at the University of Pretoria, which he completed in 2002 with a doctorate entitled 'Indicators of corporate social performance in South Africa.' Through his doctoral studies, Derick realised that the best way of shaping the debate on corporate citizenship in South Africa was to establish a university-based centre focusing on research and teaching on the broad topic of corporate responsibility and governance.

Derick joined the University of South Africa in 2002 as the founding director of the Centre for Corporate Citizenship (CCC). He has contributed on a variety of levels, both locally and internationally, towards advancing the field of corporate responsibility. His roles in the Global Reporting Initiative, the Globally Responsible Leadership Initiative, the United Nations Global Compact, the Johannesburg Stock Exchange Social Responsibility Investment Index (JSE SRI Index), King III Commission and, more recently, as a member of the working group of the Integrated Reporting Committee of South Africa are indications of his passionate commitment. He successfully built the CCC to a point where it is now regarded as a leading African institute dealing with teaching and research in the field of corporate citizenship and corporate governance.

Later, and after dealing intensely with corporate responsibility practices, codes, standards and reporting, he concluded that a lack of leadership is one of the critical issues confronting the global community. His view is that 'moving beyond compliance is possible only if you have leaders who are deeply concerned about the world we live in and how the business sector can contribute in a positive way to building sustainable future societies.' The quest to develop the next generation of responsible leaders has become his mission in life and he was given the opportunity to establish the Albert Luthuli Centre for Responsible Leadership (CRL) at the University of Pretoria in February 2009. The

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