Renewable Variable Speed Hybrid System

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Abstract

At present many remote and Island communities rely solely on diesel powered generators to provide electricity. Diesel fuel is both expensive and polluting and the constant speed operation of the diesel engine is inefficient. In this thesis the use of renewable energy sources to help offset diesel fuel usage and an alternative way of running the diesel generator with the aim of reducing electrical energy costs is investigated.

Diesel generators have to be sized to meet peak demand, in one or two diesel generator island grids, these generators will be running at a fraction of maximum output for most of the time. A new variable speed diesel generator allows for a reduction in fuel consumption at part load compared to constant speed operation. Combining the variable speed diesel generator with renewable generation should maximise the diesel fuel offsetting of the renewable source due to the increased efficiency at low loads.

The stability issues of maintaining transient performance in a renewable variable speed hybrid system have been modelled and simulated. A control strategy has been developed and the use of energy storage as a buffer for any remaining stability problems has been explored. The control strategy has then been experimentally tested along with one of the possible energy storage solutions.

An economic feasibility study has been performed on a case study community to validate the main aim of this research of reducing the cost of electrical energy in diesel generator grids.

Declaration

I hereby declare that this thesis has been composed by myself, that the work is my own and that the work has not been submitted for any other degree or professional qualification.

Paul Stott, October 2010

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Nomenclature

Roman letters

A p-n junction ideality factor

A area, m^2

C_p coefficient of performance

C_p power cost

C_w storage cost

C_m maintenance cost

C scale parameter

C capacitance, F

Ch channel

d distance between plates

D duty

E_G Band-gap energy

E energy, J

F frictional force, N

I current, A

I_{ph} cell photocurrent

I_{rs} cell reverse saturation current

I_{scr} cell short circuit current

I_{rr} Reverse saturation current at T_r

I inertia, Kg/m^2

J inertia, Kg/m^2

k Boltzmann constant

k_i short circuit current temperature coefficient

k shape parameter

k_t motor torque constant

m modulation index

n_p number of parallel cells

n_s number of series cells

P_w wind power, W

P_{demand} demand power

p.f. power factor

q charge, C

Q reactive power, var

R radius, m

R resistance, ohms (Ω)

S solar radiation, mW/cm^2 or W/m^2

S apparent power, VA

T temperature, K

T_r cell reference temperature

T_e Electrical torque

T_m mechanical torque

T_{wt} wind turbine torque

U wind speed, m/s

V wind speed, m/s

V voltage

Greek letters

ε permittivity, F/m

λ tip speed ratio

ρ density, Kg/m3

σ variance

φ phase angle, degrees

ω rotational speed, radian/s

η efficiency

Abbreviations

AC Alternating Current

BESS Battery Energy Storage System

BNC Bayonet Neill-Concelman

BMS Battery Management System

CAES Compressed Air Energy Storage

CHP Combined Heat & Power

COE Cost of Energy

DC Direct Current

DG Distributed Generation

DoD Depth of Discharge

GTI Gas Technology Institute

GUI Graphical User Interface

HOMER Hybrid Optimisation Model for Electric Renewable

IC Internal Combustion

IGBT Insulated Gate Bipolar Transistor

LE Low Emission

LED Light Emitting Diode

NG Natural Gas

NPC Net Present Cost

NREL National Renewable Energy Laboratory

MPPT Maximum Power Point Tracking

PC Personal Computer

PI Proportional Integral

PMG Permanent Magnet Generator

PMM Permanent Magnet Motor

PMSG Permanent Magnet Synchronous Generator

PS2 Playstation2

PSB Polysulphide Bromide Battery

PV Photovoltaic

PWM Pulse Width Modulation

RMS Root Mean Square

RPM Revolution per Minute

SC Super Capacitors

SMES Superconducting Magnetic Energy Storage

SMPS Switched Mode Power Supply

SoC State of Charge

TSR Tip Speed Ratio

TV Television

VRB Vanadium Redox Battery

VRLA Valve Regulated Lead Acid

VSDG Variable Speed Diesel Generator

VSIG Variable Integrated Diesel Generator

VSWT Variable Speed Wind Turbine

VVVF Variable Voltage Variable Frequency

WECS Wind Energy Conversion System

WT Wind Turbine

1 Introduction

Across the globe, there are thousands of communities that either have no electrical supply or rely on diesel generators, because connection to a larger grid is either uneconomical or impractical.

Areas that typically operate stand-alone grids are generally: remote or inaccessible regions, usually in harsh environments where there are few inhabitants (i.e. communications outpost); islands that are too small to have their own conventional power plants and are too far away from the mainland; and developing countries where many communities are rural.

Although conventional diesel generators are cheap to acquire, lifetime diesel fuel costs are high, resulting in a kWh price three or more times greater than that of the mainland (Muck Island 0.35Eur/kWh, Mainland 0.1Eur/kWh [1]).

The ever growing demand for diesel from all around the world indicates that the price of diesel is likely to increase further. Increases in fuel prices have a double impact on remote areas requiring fuel for their diesel generators, since the fuel transportation costs are also likely to increase.

To offset the cost of diesel produced electricity, renewable generation has been integrated into some of these systems to create hybrid power systems. The locations where off-grid power is needed often have good renewable resources. Islands nearby have wave and tidal energy. Solar energy is available everywhere, but developing nations close to the equator naturally have better resources. Hydro energy can be found in some regions, but these are more site specific.

The majority of hybrid power systems are found on islands, consisting of wind and diesel generators. Wind turbines are currently a popular choice, because they are the most mature and economic form of renewable generation and islands often have a good wind resource.

Integrating intermittent renewable generation into large mainland grids can cause stability problems and these problems are only amplified in the small diesel generator grids where the proportion of renewable generation is normally higher. Depending on the level of renewable penetration in the hybrid system, energy storage or controlled loads may need to be installed.

Diesel generators work most efficiently at full load (η=32% [2]), but community loads vary throughout the day. Diesel generators are sized for peak load demand, which only occurs a few times a year, hence the diesel gensets operate uneconomically. The introduction of renewable generation will only add to this problem through reducing the load seen by the diesel generator. This will further decrease the average efficiency (11% @ 20% nominal load [2]) since the fully sized generator will still be needed for when no renewable generation is available. A large proportion of the losses at part load are associated with the constant speed operation of the diesel engines. Diesel generators are run at constant speed so that they produce constant frequency (50 or 60Hz) for the grid. A new type of diesel generator that operates at variable speed is more efficient at part load. It is able to run at variable speed by using power electronic converters to change the VVVF (Variable Voltage Variable Frequency) produced by the generator to the constant voltage and frequency of the grid. While variable speed generators reduce fuel use, it has been shown in this work that the stability under heavy load transients is reduced, compared with constant speed diesel generator operation.

There are also a number of new energy storage devices on the horizon which may go some way to levelling the load transients seen by the variable speed generator thus improving its stability. These load levelling devices could help facilitate the integration of renewable sources in a hybrid power system, which will help increase fuel saving potential by offsetting power produced by the diesel generator and reducing the overall cost of electricity.

1.1 Aim of Thesis

The aim of this thesis is to investigate the operation and economics of a hybrid power system deploying Variable Speed Diesel Generator (VSDG) and renewable sources. Objectives include:

- To assess the feasibility of such a system
- To create a control scheme for the system
- To experimentally verify the system and its control
- To overcome any operational difficulties of a VSDG in a hybrid system
- To optimise the hybrid system economically
- To create a simple set of design calculations for the Supercapacitor system sizing

1.2 Thesis Outline

Chapter 2 will explain the diesel generator and its use in the generation of electricity. The advantages and disadvantages of the different modes of operation, constant and variable speed, are outlined. A literature review of previous work on variable speed gensets is also included.

Chapter 3 looks at the use of hybrid power systems in supplying off grid communities. The different components that make up a hybrid system are introduced and a literature review of different hybrid system solutions is presented. Finally, a case study community hybrid power system is presented to be used later for comparison.

In Chapter 4 the feasibility of variable speed operation of the diesel generator is critically assessed both on its own and in a hybrid system. The first feasibility model calculates the potential fuel savings over a typical year's operation. An economic model, HOMER (Hybrid Optimisation Model for Electric Renewables), is then used to calculate expected system lifetime cost under various sensitivities and hybrid system topologies.

In Chapter 5 a model of the proposed fully integrated variable speed hybrid system is developed and simulated under three different time ranges: sub-transient, power system dynamics and power balance.

To validate the proposed hybrid system and its control strategy, experimental work was done using low power electromechanical test rigs, which is described in Chapter 6.

In Chapter 7 preliminary results of experimental work using a commercial VSIG from Cummins Generators technology has been detailed. Using actual equipment removes any modelling uncertainty or limitation in the simulated components.

The final chapter summarises the work done in this thesis and presents the contributions to knowledge made.

2 Diesel Gensets

Fixed speed diesel generators also known as “diesel gensets” have been in operation supplying electrical power for over a century. This chapter will describe the market for diesel gensets, a typical system and its advantages and disadvantages. The method of operating the diesel genset at variable speed will be explained and compared with the standard constant speed case. The conditions where the Variable Speed Diesel Generator (VSDG) performs best and should be considered are also explored.

2.1 History

Across the globe, diesel engines are used to create electricity in their hundreds of thousand, ranging in size from kW to MW systems [5]. One of the main uses for diesel generators is supplying base-load for a stand-alone grid, where connection to a national grid is either uneconomical or impractical. As well as providing base load, diesel gensets are also used for load management, emergency power, ancillary services, micro-grids and combined heat & power (CHP).

Areas that typically operate stand-alone grids are generally: remote or inaccessible regions usually in harsh environments where there are few inhabitants (i.e. communications outpost etc); islands that are too small to have their own conventional power plants and are too far away from the mainland; and developing countries where many communities are rural.

The world market for Distributed Generation (DG) is vast, the estimate for England and Wales in 2008 was 12GW [3]. There are large areas of the world where DG is considered preferential. Arctic regions are thought to be the largest and Canadian territories alone import 400 million litres of diesel each year [4]. Taking Alaska as a prime example of an Arctic region, it has 175 villages off the main grid. Almost all are supplied by electricity produced from diesel generators. In 1988, the installed capacity in Alaska was 259MW growing 10% annually [5]. In 1997, $162 million of revenue was collected in Alaska from municipal utilities in the 151-300kW-power system range.

Although conventional diesel generators are cheap to buy, the diesel fuel lifetime running costs are expensive, resulting in kWh prices three or more times greater than mainland rates, e.g. Muck Island 0.35Eur/kWh, Mainland 0.1Eur/kWh [1]. The current trend of ever increasing fuel and energy prices will only exacerbate this.

Most communities using diesel gensets need government help with subsidies and interest free loans to help towards the stock buying of large quantities of diesel fuel, so that electricity can be brought down to a reasonable price. This shows that there is a definite need to reduce the basic cost of electricity production for diesel based grids.

A new design in the field of diesel generators promises to help reduce fuel use for the majority of cases and lower overall lifetime costs. Variable speed diesel generators promise better fuel economy at part load, which is where most diesel generators spend the majority of their life. These generators are not fully proven in the field of renewable hybrid systems and further investigation under transient conditions is required.

2.2 Set-up for a Diesel System

The typical set-up for a diesel generator system is displayed below in Figure 2.1. The main components of the system are the diesel engine, synchronous generator and fuel tank.

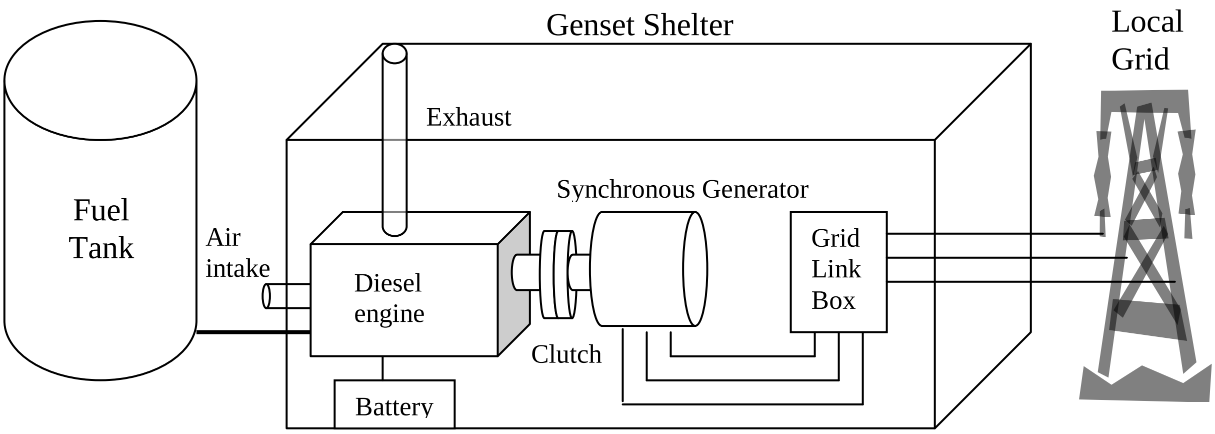


Figure 2.1– Diesel Generator System

The reciprocating internal combustion diesel engine operates on a four-stroke cycle (intake, compression, combustion and exhaust). The crankshaft of the diesel engine is connected to the rotor shaft of the synchronous generator either by a solid shaft or a clutch, both of which will be supported by bearings. A battery is needed to power the diesel engine starter motor and the electrical machine excitation. Once the system is up and running, power from the generator can be fed back into the exciter and used to recharge the battery. Standard diesel generators are fitted with synchronous generators [6] and consequently are controlled to run at a constant speed to guarantee constant electrical frequency. The power from the synchronous generator is connected to the grid through switch, to allow isolation and off-grid start up, with protection usually housed in a connection box.

The whole system is housed in a weatherproof building or container that has been specially modified with air intake and exhaust pipes and some soundproofing is included.

2.3 Constant speed diesel gensets

2.3.1 Advantages

Diesel generator technology has not changed much since the early 1900s, other than a marked improvement in diesel engine emissions and performance and the advent of self-excited synchronous generators. The capital cost of a complete diesel power system is also low compared to other distributed generation (£100-500/kW diesel genset or £200-1000/kW installed, £4-20 per gallon or £0.8-4.4 per litre fuel storage tank[7]) allowing communities to own them outright without loans or government help. They can be easily transported and installed which reduces setup time and costs. Running costs will vastly outstrip any capital cost over the lifetime of the system. Operation is very simple and with regular maintenance is very reliable, which is a major concern for remote location where parts are not easily available. In some cases, it can take weeks for a new part to arrive due to bad weather. Diesel engines can normally be repaired and maintained by someone in the local community, such as a trained mechanic, which adds to the self-sufficiency these communities desire. Diesel gensets are efficient in and around the rated load allowing minimum fuel use.

2.3.2 Disadvantages

Although diesel gensets are a reliable mature technology, they suffer from a few fundamental problems which have not been properly addressed. At full load, constant speed diesel generators run at maximum efficiency, but unless the local demand is large enough to require multiple Gensets, it is likely to spend most of its operational life partly loaded. Figure 2.2 illustrates the load variation for a small community. With the variation in daily, as well as seasonal load, it is not possible to avoid low loading of the diesel gensets, unless a large number of low power units are installed (e.g. 25% of full load).

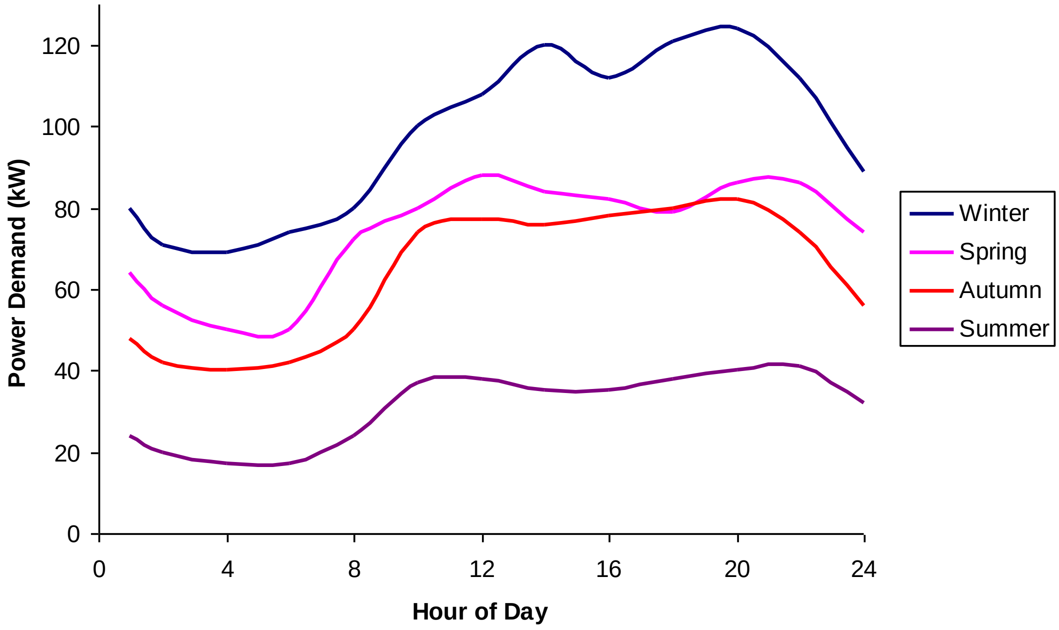


Figure 2.2- Small residential community load in Norway [8]

Fuel consumption per kW produced is seen to increase at lower loads and fuel consumption at no load is still 15-30% of the full load point [8]. Universal fuel consumption vs. load is shown in Figure 2.3 for large and small engines.

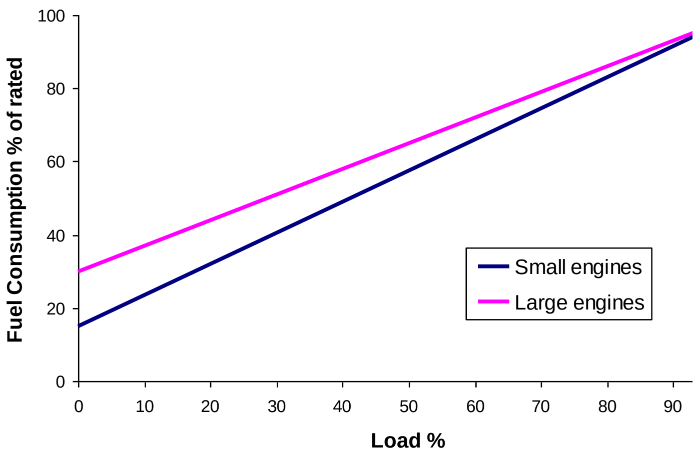


Figure 2.3 – Fuel Consumption [8]

Another matter that can compound this problem is the fact that most engine manufacturers recommend a minimum loading, which can be as high as 40% of rated capacity, in order to prolong diesel engine lifetime [10]. To achieve this, dump loads may need to be installed at extra cost to the consumer. The deterioration of the diesel engine lifetime at low loads transpires from build up of unburnt fuel inside the engine (pistons, cylinders etc).

Although diesel gensets are cheap to buy, there are running costs and environmental consequences to consider. The high price of diesel fuel is aggravated in many cases by the additional transportation costs to remote areas. Diesel generators need regular maintenance, as do fuel storage tanks. Therefore, the cost of electrical energy production ends up being several times higher than that found on large mainland non diesel grids.

Diesel engines burn fossil fuel, which releases harmful emissions into the atmosphere and depletes the earths limited stored resources. Even with the recent advances in reduced emission, diesel engines still produce a high level of pollutants per MWh. Their CO_2, NO_X, SO_2 and PM-10 emissions are amongst the highest, with only CO emissions being around par with conventional generation plant [11].

POLLUTANT kg/MWh	CO_2	NOx	SO^2
ICE Diesel	773	18.64	1.36
ICE Natural Gas (NG)	545	24.09	negligible
LE ICE (NG)	500	2.73	negligible
Micro turbine (NG)	818	0.64	negligible
Fuel Cell	636	0.02	0.00
Biomass	0 - 1045	0.14 - 2.7	0.14
PV	0	0	0
Wind	0	0	0

Table 1– Distributed generation emissions (NG = Natural Gas, LE = Low Emission)

Other environmental dangers that arise from using diesel as the primary energy source come indirectly from accidents such as spillages during transportation. Diesel engines can also be noisy and cause vibrations, but advances in diesel engines and mounting technologies have reduced these impacts along with soundproofing measures.

2.4 Variable Speed Diesel Generator (VSDG)

Research into VSDGs was motivated by the desire to improve performance at part load, in terms of efficiency and running cost. VSDG have been proposed as a technological solution for the diesel generator market for over a decade [12]. With recent cost reductions in power electronics, the VSDG has started to make more economic sense. As a consequence, they are now commercially available and are being manufactured by Cummins Generators Technology and Marathon Electric.

2.4.1 Advantages

The main impetus for the development of the VSDG is to reduce fuel consumption. This is accomplished by running the engine at the most efficient point on the torque speed curve for a given power demand.

At low loads, the speed of the generator will be reduced, ensuring the engine is running optimally in terms of fuel economy [13], which is shown experimentally in [10]. The engine can also be run at much lower loads without the detrimental consequences experienced by constant speed operation. The engine performs fewer rotations per minute and, consequently, less combustions than constant speed operation at the same load. As a result, the combustions are fuller, thus alleviating unburnt fuel build up. Due to the fuller combustion of the fuel, the engine exhaust is less polluting. The operating set points can also be augmented to make engine pollution the most important criteria.

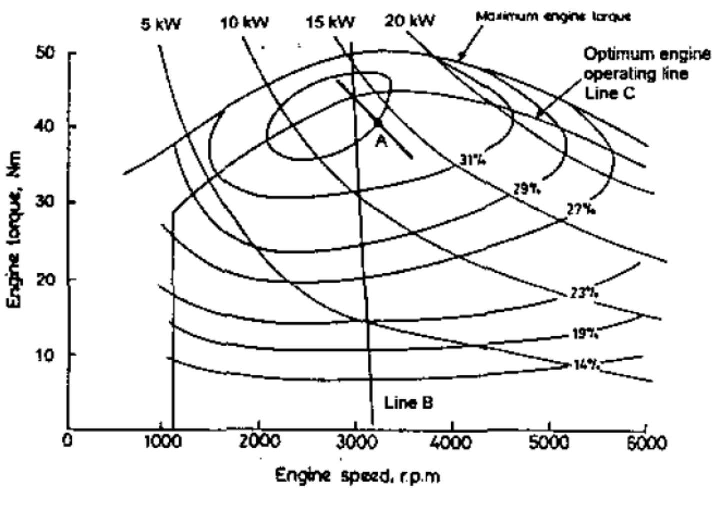


Figure 2.4– Optimum Engine efficiency [14]

Figure 2.4 illustrates the variations in efficiency of a 20kW IC (internal combustion) engine over its full dynamic range. The circular bands mark off the different efficiency zones. Line C follows the optimal variable speed settings, line B a constant speed of 3000rpm, which is not exactly vertical due to speed droop, and line A constant power 14kW. At a 5kW output, the variable speed operation has a 7% greater efficiency than constant speed operation. The constant speed mode of operation is never more efficient than the variable speed and only ever matches it at near full load. It is clear from this graph that variable speed operation of a diesel engine is beneficial in terms of efficiency and therefore fuel consumption. Variable speed operation also allows more power to be produced from the same sized engine in most cases, as the speed can be increased above that of the set constant speed.

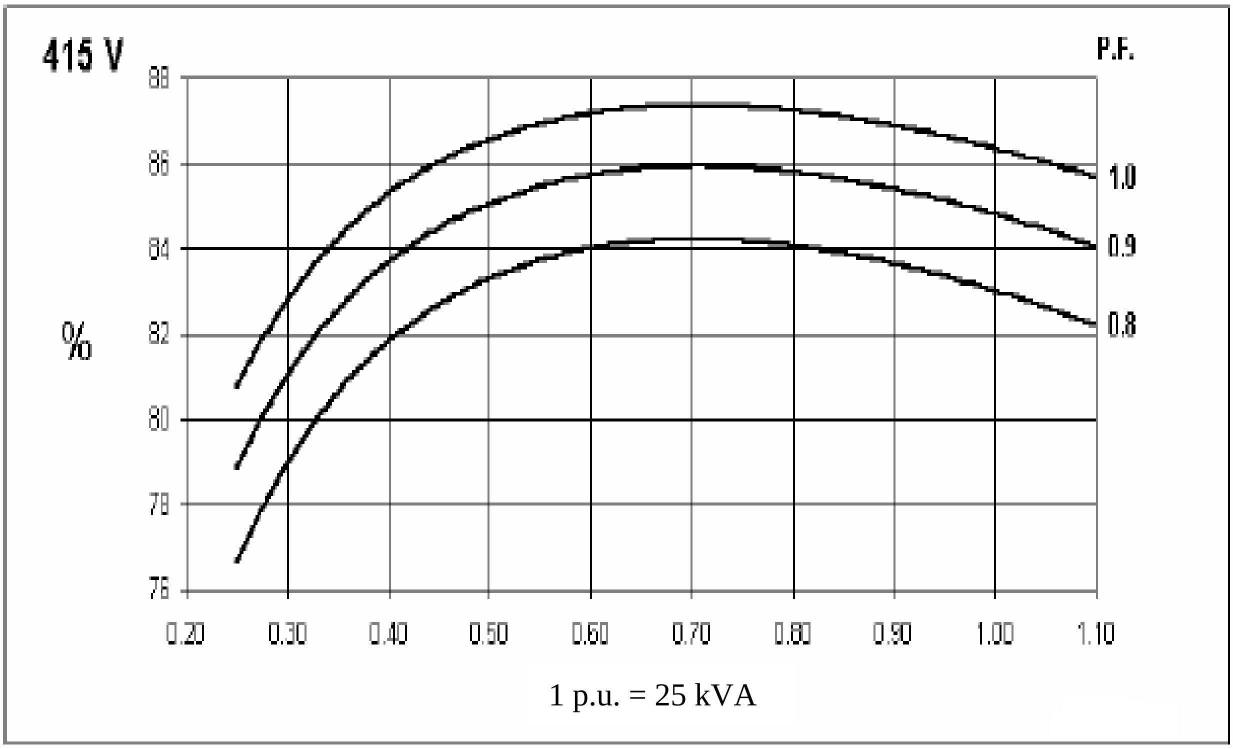
As well as being more efficient and cleaner, variable speed operation can also be quieter than constant speed, given that it runs at lower speeds when part loaded. This can be important for systems close to properties that run during the night, when the diesel engine load is likely to be low and noise pollution is more of a problem. As with the pollution control, the operating set points can also be optimised for the quietest running conditions.

A number of advantages are created by using a PMG, they can be very beneficial in stand-alone grids where there is no readily available supply of electricity for excitation. Most variable speed generator concepts [15],[16],[17] and actual systems [10],[6] use PMG. This allows them to run more efficiently, especially at lower loads when excitation power becomes a larger proportion of the power balance in a conventional generator (synchronous & asynchronous).

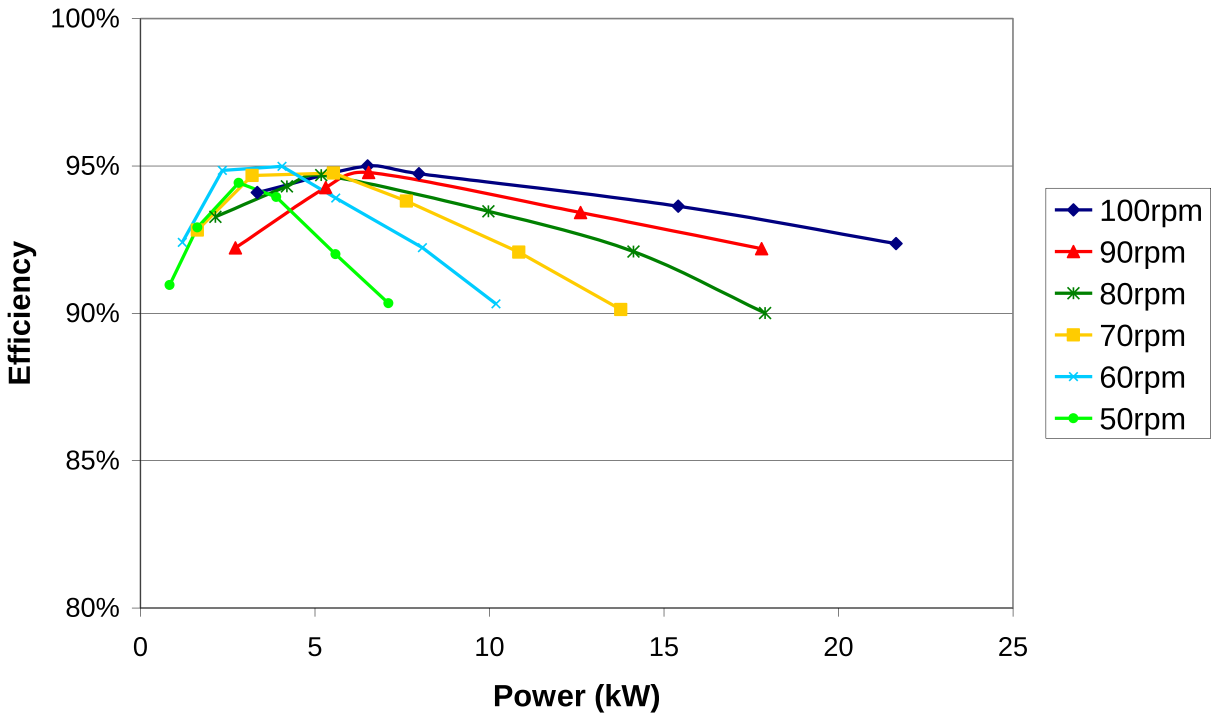
PMG have the ability to be more reliable than conventional generators, because they are selfexcited and can be mounted directly on to the engine crankshaft, which removes the slip rings and bearings fitted to standard genset that would otherwise need regular maintenance.

Comparing Figures 2.5(a) and 2.5(b) it can be seen that the permanent magnet generator is more efficient than the synchronous generator for all load situations, At part load, the Permanent magnet generator performs much better than the synchronous generator, never dropping below 90% efficiency which is greater than the maximum achieved by the synchronous generator. Using a PMG gives the complete generator and converter system an overall efficiency of around 85-90% (0.95*0.93=0.88), which is comparable to a synchronous generator on its own.

The electrical machine efficiency plots are for specific machines and are only meant to illustrate the trends in the different designs.



(a) Synchronous generator [18]



(b) Permanent Magnet [19]

Figure 2.5– Generator efficiency

2.4.2 Disadvantages

All variable speed generators need converters to control the voltage and frequency of power supplied to the grid. A good converter can run at up to 95% efficiency, but all have losses associated with switching devices and static elements such as capacitors, diodes and inductors. Permanent Magnet Generators (PMG) are more efficient than other generators, owing to their absence of electrical excitation, this allows them to reinstate some of the loss from the converter.

The additional cost of power electronics and PMG dramatically increases the cost of the diesel genset, but also increase the control requirements, complexity and therefore total cost.

The dynamic performance of the VSDG is a potential disadvantage, as it can be compared at any given instant to a constant speed diesel generator with the maximum output related to the set rotational speed. Therefore, the generator seems to increase in size as the rotational speed increases up to the maximum power.

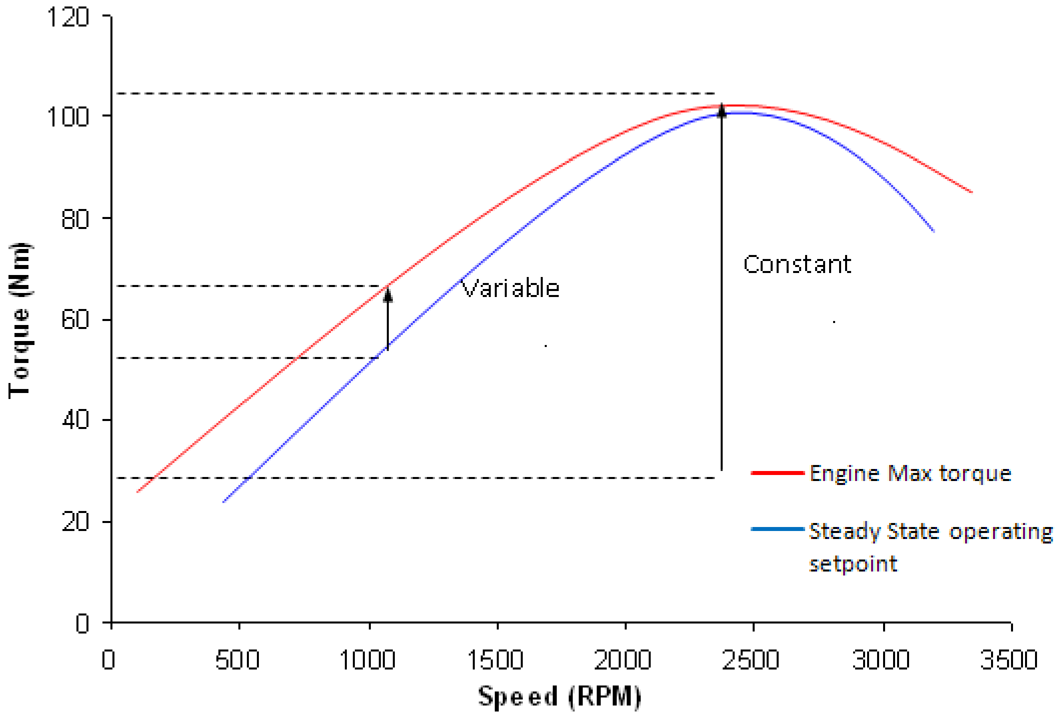


Figure 2.6 – Diesel Generator Loading

The additional torque available at any given moment is the diesel engine maximum power (top line) minus the steady state operation set point (bottom line), demonstrated by the variable speed arrow in Figure 2.6.

The torque available to meet step load increases for the constant speed generator (right arrow) at the same power starting point as the variable speed operation (left arrow), is much larger. The instantaneously available torque significantly affects the generators dynamic stability. If a step load above the available power is applied to the generator, it will not be able to meet the demand quickly and the diesel engine could stall causing a blackout. For a small generator sized for a community of 10-15 households, the equivalent demand of two electric kettles (3 to 4kW) being switched on or a small drop in wind speed for a high penetration wind-diesel system could be enough to seriously compromise the VSDG stability. To compound matters any load increase may initially decrease the engine speed leaving less available power to meet the load change. If a step load increase is large enough to use all the immediately available power, the generator would then be in a very dangerous/unstable condition, as it would be unable to accelerate to the new set speed, and even a small load increase after that would be capable of crashing the system.

VSDGs are a new technology and therefore the reliability of the systems has a level of uncertainty attached to it. This is a significant obstacle to up take, especially in remote communities where it would be used as the main source of power.
Although power electronics are generally seen as reliable and require very little if any maintenance, their addition can also take away the communities ability to fix faults impacting on their independence. The modularity of many power electronic components also means that even if a suitably qualified person is available to find faults and carry out repairs, spare parts would need to be readily available. As these components are often expensive, they are not likely to be stockpiled and so they would need to be ordered in. Many power electronic components are in short supply and therefore can have long lead times adding to the transport delays, which can also affect these remote areas.

2.5 Summary

To summarise, conventional diesel gensets are a reliable but expensive way to supply electricity. The main reason for their expense is the price of diesel fuel, which is further aggravated by the inefficient running of the diesel engine at part load. To overcome this problem, the running of the diesel engine at the optimum speed for the load (i.e. variable speed) has been suggested. Although this is not a new idea, the increased cost of the variable speed diesel generator, mainly because of the need for power electronics, is only just starting to be offset by the fuel savings. Variable speed operation of the diesel genset is expected to be beneficial for most offgrid community applications.

3 Hybrid Systems

As stated previously, a lot of communities that rely on diesel gensets need help through government subsidies and interest free loans to bring the cost of electricity down to a reasonable price. One way of reducing the cost is to reduce the diesel generator load and hence fuel consumption by meeting some of the demand through renewable energy.

Wind-Diesel hybrid systems can offer substantial savings and by 2001 Alaska had 3 pilot projects up and running. Alaska being situated on the NW coast of America has good resources of renewable energy, mainly in the form of wind, and has the largest areas of class 7 wind power (mean wind speed above 8.8 ms^{-1} at 50m) in the United States [20]. Wind-diesel systems have been in operation from as early as 1977 in Clayton, N.M., U.S [8]. In the Highlands & Islands of Scotland wind-diesel systems are in use, one example being Muck Island in the Hebrides [1].

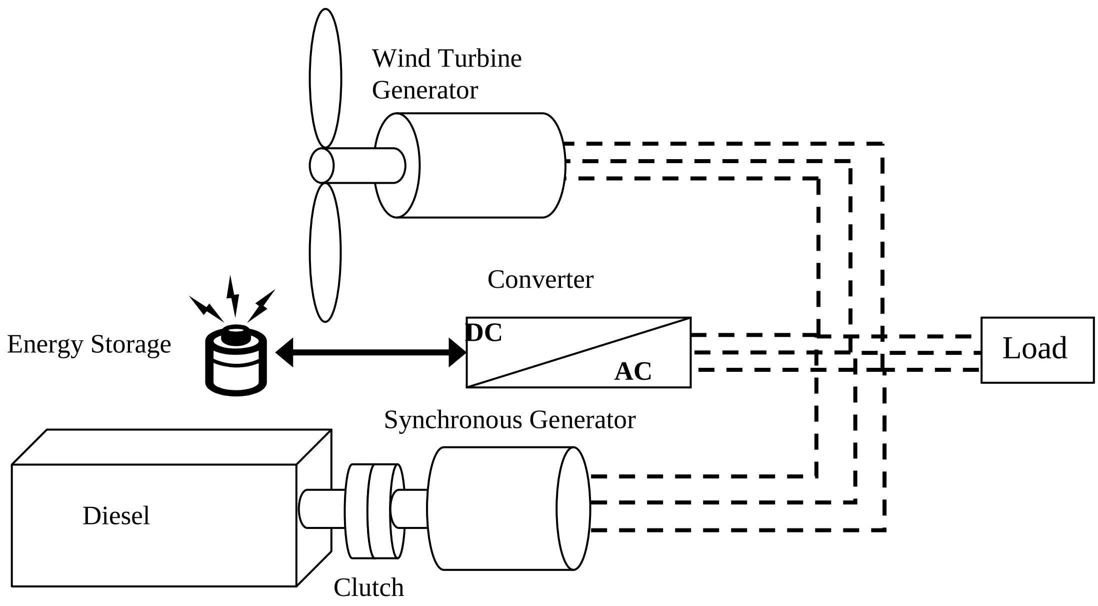


Figure 3.1– Typical Hybrid system

A typical hybrid systems setup has each component connected to the grid with its own individual synchronisation. The system normally have a constant speed diesel genset providing base load and a grid connected wind turbine usually with some form of energy storage as shown in Figure 3.1. There are many different permutations to hybrid systems and factors that affect them are natural resources and renewable power penetration levels.

The natural resources that can be harnessed include

- Wind
- Solar
- Hydro
- Wave and tidal
- Biomass/fuels

Some hybrid systems will have a combination of renewable generators either because of the abundance of the resource or the natural balance that occurs between them. As the renewable penetration levels increase so does the complexity and cost of the system, but also the possible fuel savings and consequent running costs decrease.

In low to medium renewable power penetration hybrids, the diesel generators remain on and run full time [21]. This only allows limited savings to be made due to the problems mentioned in the diesel generator section about fuel consumption per kW increasing at lower loads. High penetration hybrids tend to switch off the diesel generators when the renewable power can match the load and thus much greater fuel savings can be observed. If the power available from renewable sources exceeds the load demand, the control of the system becomes a lot more complex.

There are three ways to handle this extra available power

1. Power limitation of renewable devices using special machines or control programmes
2. Dump loads, resistor banks or water heating etc
3. Energy storage of the excess energy.

There are three levels of complexity in hybrid systems

1. Basic systems have stand alone generators where the renewable generator acts as a negative load on the grid. No additional hybrid system control is implemented and no energy storage is needed, as the renewable generation does not exceed the load.

2. Intermediate systems may still have stand alone generators with no control linking the diesel to wind turbine, but dump loads are used to maintain system stability. This is needed because of the increased renewable penetration.
3. Advanced systems can be fully integrated with renewable power, genset and energy storage all feeding the same inverter and controlled to match demand. Most advanced systems will have energy storage, because of the high renewable penetration level.

Originally, when wind-diesel hybrids were first developed, fixed speed diesel generators and wind turbines were used. As technology advanced and the benefits of variable speed wind turbines became apparent, hybrid systems incorporating them arose [22]. Standard diesel gensets, variable speed wind turbines and other devices can be connected through the power electronic converters to a common dc-link. A dc/ac converter is then used between the common dc link and the grid. The benefits of not having a direct connection with the grid are quicker and easier start up of the genset as synchronisation with the grid is no longer required [23]. In [17] the idea of parallel operation of a variable speed wind turbine and diesel generator with separate converters and energy storage is developed. One of the considerations is that the engine may not be able to supply load under sudden loses of renewable resource. Energy storage could be used to level out fluctuations in renewable power to alleviate this problem.

The sizing of hybrid systems is often the critical stage that determines if a system will ultimately be successful or not. Each section of the hybrid system effects and interacts with another. If the genset rating is too high, fuel will be wasted; if the rating is too small, there is the risk of regular brownouts, engine stall or local grid failure. The renewable resource at the site and grid loads have to be extensively researched and monitored before any choices are made, so that a cost-optimised system can be installed. Choosing the right wind turbine, to use is more complicated than just looking at the average wind speed as likely periods of over-production have to be assessed, so that energy storage can be accurately sized.

There is an assortment of methods to aid in the design of hybrid systems. Two different options are reviewed in [24] for a PV-Wind diesel hybrid system with storage.

One such is a software based system called HOMER, which stands for Hybrid Optimisation Model for Electric Renewables and was developed by the National Renewable Energy Laboratory (NREL) [80]. HOMER still requires the same, if not more meteorological and manufacturers data as other methods, but all the complicated calculations are hidden away and there is a wider choice of devices available to simulate.

The program can quickly simulate a year's operation and find the optimal number of wind turbines and storage size. It does have its limitations as not every energy storage, prime mover or renewable device is catered for. HOMER has a user friendly Graphical User Interface (GUI) system.

Hybrid 2 is another model developed by NREL. It allows more detailed simulation to be run for long-term performance and economic analysis [25].

The different computer models can be split up into time-series and statistical simulations. Detailed time series models do give more accurate results, but information needed for them is not always available, or easy to find.

The software models concentrate on

- Performance – system stability and power quality, etc.
- Optimisation – costs and sizing
- Control – finding the most efficient strategies

In [26], a probabilistic method for evaluating the performance and reliability of wind-diesel hybrids is presented. It calculates expected annual wind and diesel production along with loss of load probability and expected unserved energy. Information used includes: the diesel fuel consumption curve, upper & lower power limits, wind turbine characteristics, wind power limiting constraint and hardware availability. In [27], there is a similar model, but instead of using a probabilistic method it uses a Monte Carlo technique. It is stated that the Monte Carlo method is superior due to the more detailed diesel generator unit commitment scheduling. This allows the diesel generators to be turned off when there is enough wind, etc.

The reliability of a stand-alone grid is a key issue, because they are often located in remote and inaccessible regions. This is one of the main reasons why the take up of hybrid systems has been slow, even with the substantial cost benefits available. If a component fails on an Island hundreds of miles from the mainland, or in areas within the Arctic Circle, it could be days or even weeks before a part or technician arrive. As standard diesel gensets are a simple mature technology, they are extremely reliable to begin with, given a little constant maintenance. If a breakdown does occur, a local mechanic is likely to be able to quickly fix the engine.

Wind turbines and other renewables represent the unknown and communities may not trust or want to rely on them. If anything does go awry, it is unlikely that the tools and skills needed to fix them would be available loacally.

These remote power systems often have to work in extremely harsh environments, such as

- Corrosive sea water spray
- Prolonged Sub-Zero temperatures
- Humid dusty climates

Operation in such environments will lead to increased mechanical and electrical malfunction and faults.

Wind turbines in hybrid power systems may therefore have different design requirements as discussed in [28]. Access to site can be a key aspect in sizing the wind turbine. Large cranes are needed to install wind turbines of above 50kW. Access can be affected by lack of roads, steep rocky terrain, sand, ice and deep snow. Wind turbines with direct drive permanent magnet generators are regarded as more reliable than gearbox driven generators, as the gearbox is often considered the weak link. They also have to be well sealed to keep out the elements, as any damage/wear that does occur may not be easily repaired without complete disassembly for most generator topologies. Ease of onsite maintenance and repair is an essential matter for most sites, since manufacturers workshops are likely to be some distance away. The wind turbine should therefore be designed for trouble-free maintenance with easily accessible parts and limited use of heavy equipment. Tools and manuals should be kept on site along with any lifting equipment necessary for basic maintenance.

Controlling the hybrid power system can involve sophisticated scheduling and control algorithms. Variable speed and pitch control can be utilised successfully to quickly limit power from a wind turbine. This effectively works like a dump load and requires no extra hardware only software changes.

Two 288kW power reducing wind turbines are used in [25] along with two 580kW diesel generators. This system achieved sustained penetration levels of 50% in high wind periods with peaks of up to 70%. This was achieved with a strategy of 100% spinning reserve, one 580kW diesel genset, and a soft minimum diesel loading of 40%. Fuel savings seen were limited, but the system was still deemed financially viable.

A system on Osmussaare Island [29] also uses a power limiting wind turbine specifically controlled for hybrid systems thus alleviating dump loads and energy storage. The wind turbine is produced by Pitchwind [30] and is connected to the diesel genset through a DC-link that allows easier control of the diesel engine.

In [31] it states that most of the power quality issues can be improved through the use of a power electronic converter. Given that standard constant speed gensets and wind turbines can meet limits imposed on electrical generators, variable speed devices with power converters should be able to as well. The operation around cut-in gives the largest deviation in transient performance and the frequency variations are sensitive to the turbine inertia.

By combining the fuel reduction benefits of the VSDG and use of renewable hybrid systems, the cost of electricity should be reduced further. The VSDG is ideally suited to make full use of the renewable generation, because of more efficient operation at part load, which is where a diesel genset in a hybrid system will spend most of its time. Systems using VSDG are also capable of supporting much higher renewable penetration levels, due to the lower minimum loading capability and so less renewable power will have to be shed or less energy storage will be required.

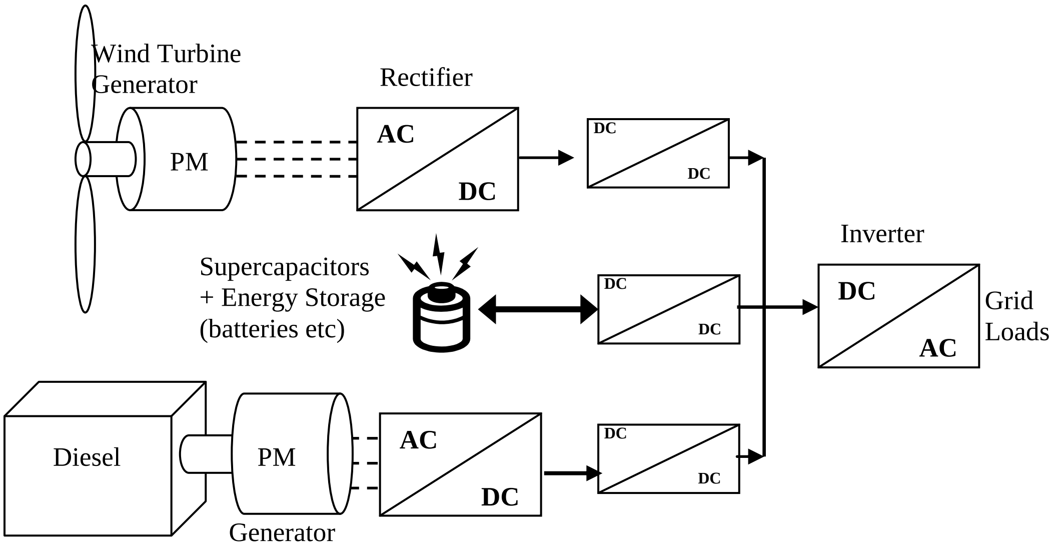


Figure 3.2- Variable speed fully integrated hybrid system

The advantages of a fully integrated system, shown in Figure 3.2, include modularity and flexibility, so that many different generation forms can be incorporated. The inverter and diesel generator are sized to meet the load while the renewable generation can be specified as wished (most economic, highest penetration/cleanest, to budget). Having a single grid inverter decreases control complexity and improves stability, as inverter to inverter interactions are avoided. The DC/DC converters change the generators output voltages to that of the common DC link. The overall system should also be cheaper by avoiding the need for each energy source to have its' own inverter because of the shared use of the common inverter.

3.1 Power Generation

Power generation can be split up into two sections dispatchable and intermittent. Dispatchable power generators can be controlled to provide the power required when needed. These forms of generation are normally fossil fuel powered (coal, nuclear, gas, oil, diesel, petrol, etc.), or can be energy storage based (Fuel cells, hydro dam, biofuels, etc.). Intermittent power generators have only a limited amount of controllability and cannot be dispatched when needed. They are epitomised by renewable power sources (wind, wave, tidal, solar, hydro stream etc).

3.1.1 Dispatchable generation

Most hybrid power systems will have some form of dispatchable power generation because supplying the whole system load with renewable sources is not economical. This is due to two reasons;

1. Ensuring renewable generation always exceeds load demand requires gross over capacity of the renewable system
2. The need for dump loads or energy storage to deal with the excess power when it is produced. The cost of energy storage for a system with a more closely matched energy production and demand will still be substantial, as energy may need to be stored for long periods of time.

Table 3.1 lists the profile of some of the available dispatchable generation suitable for hybrid power systems. The main source of power generation for the target communities is the diesel generator. With some modification, diesel generators can be run on biodiesel or hydrogen. Hydrogen can also be used in fuel cells to produce electricity more efficiently than in a diesel engine, but the cost is higher and reliability of this technology is still not fully proven in the field. Microturbines are also an option and can be run on a number of different fuels (Low or high pressure natural gas, Biogas, Flare gas, diesel, Propane and kerosene). Micro turbines suffer from the same problems as fuel cells, being high cost and as yet not fully proven in the field, but are not as efficient as other form of generation as can be seen from table 3.1.

Technology	Recip Engine: Diesel	Recip Engine: Natural Gas	Micro-turbine	Combustion Gas Turbine	Fuel Cell
Size	30kW - 6+MW	30kW - 6+MW	30-400kW	0.5 - 30+MW	100-3000kW
Installed Cost (£/kW)[1]	396-660	462-792	792-1,122	264-594	2,640-3,300
Electrical Efficiency	30-43%	30-42%	14-30%	21-40%	36-50%
Total Maintenance Costs (£/kWh)	0.0033 - 0.0099	0.0046-0.013	0.0053-0.0099	0.0026-0.066	0.00125-0.01
Emissions (gm / bhp-hr unless otherwise noted)	NO_x: 7-9 CO: 0.3-0.7	NO_x: 0.7-13 CO: 1-2	NO_x: 9-50ppm CO: 9-50ppm	NO_x: <9-50ppm CO:<15-50ppm	NO_x: <0.02 CO: <0.01

Table 2 – Non-intermittent distributed generation [32]

3.1.2 Wind

Wind Energy Conversion Systems (WECS) convert energy in the wind to mechanical energy at the rotor and then to electrical energy in the generator. The rotor blades extract energy from the wind when the wind moves over the blades in the correct direction. The wind velocity that the airfoil blades experience is a combination of the wind and rotational speed as shown in Figure 3.3.

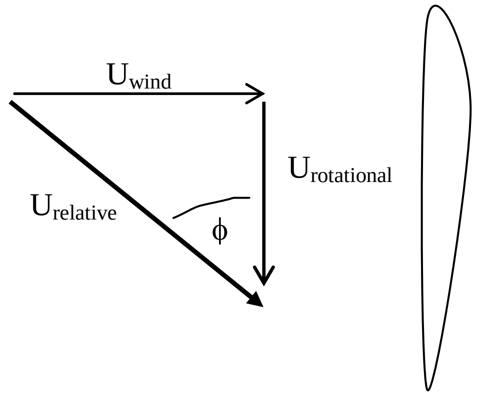


Figure 3.3– Relative Wind

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[1] Cost varies significantly based on siting and interconnection requirements, as well as unit size and configuration. An exchange rate of 1.515 $/£ has been used in this table

Wind turbines can be operated at variable or fixed speeds but technology is advancing towards variable speed because of its increased energy capture [33]. Some variable speed systems have limited ranges whereas others are fully variable. The power from the wind is proportional to the wind speed cubed and the coefficient of performance of the blades, C_p, and is calculated by

$$P_w = \frac{1}{2} \times C_p \times \rho \times \pi \times R^2 \times U^3 \quad \textbf{(3.1)}$$

ρ air density, Kg/m3
R radius, m
U wind speed, m/s

The maximum possible power extracted by the wind turbine is determined by the Betz limit, which states that the maximum conversion efficiency of a wind turbine is 59% and occurs when the wind velocity is slowed by 2/3 through the rotor [34]. The coefficient of performance, C_p, is related to the Tip Speed Ratio (λ) and a typical wind turbine C_p - λ is shown in Figure 3.4.

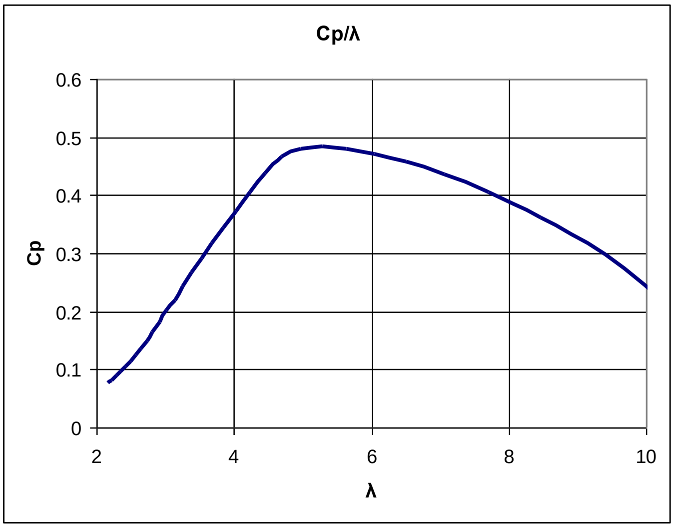


Figure 3.4– Cp - λ curve

The TSR (λ) is the ratio of the speed of the blade at the tip to the wind speed,

$$\lambda = \frac{\omega \times R}{U} \quad \textbf{(3.2)}$$

ω rotational speed, radian/s

About 86% of wind turbine technology utilise gearboxes to step up the slow rotational speed to high speed, so that conventional generators, such as the induction machine, can be used. Gearboxes are seen as the weakest link in the wind turbine design, as they are heavy and expensive components that require regular maintenance, and are susceptible to failures. Some offshore wind turbines have had substantial reliability problems with regards to gearboxes. Scroby Sands, UK had major issue with gearbox bearings and generators which has required the replacement of all the generators and the majority of the gearboxes bearings [75]. The remaining 14% of wind turbines use direct drive generators, in which a slow speed multipole generator is coupled directly to the turbine blades. ENERCON is the world leader in direct drive wind turbines [35]. Eliminating the gearbox allows greater conversion efficiency, as gearbox losses are avoided, and improved reliability. Disadvantages of direct drive are that they require specialised and therefore more expensive generators. The generators are large and heavier, which causes additional problems when it comes to transportation and placing them on top of the wind turbine tower, which also needs to be stronger to support the extra weight.

The UK wind energy resource has been stated as the best in Europe. Winds build up over the Atlantic Ocean and blow over the country from the west [36]. The west and northwest coasts of Scotland, therefore, have a very strong wind resource, as is shown in Figure 3.5 [36] in which the majority of the west coast has a mean wind speed above $7ms^{-1}$. Many of these strong wind sites also happen to be the location of small and remote islands that are candidates for wind-diesel hybrid systems.

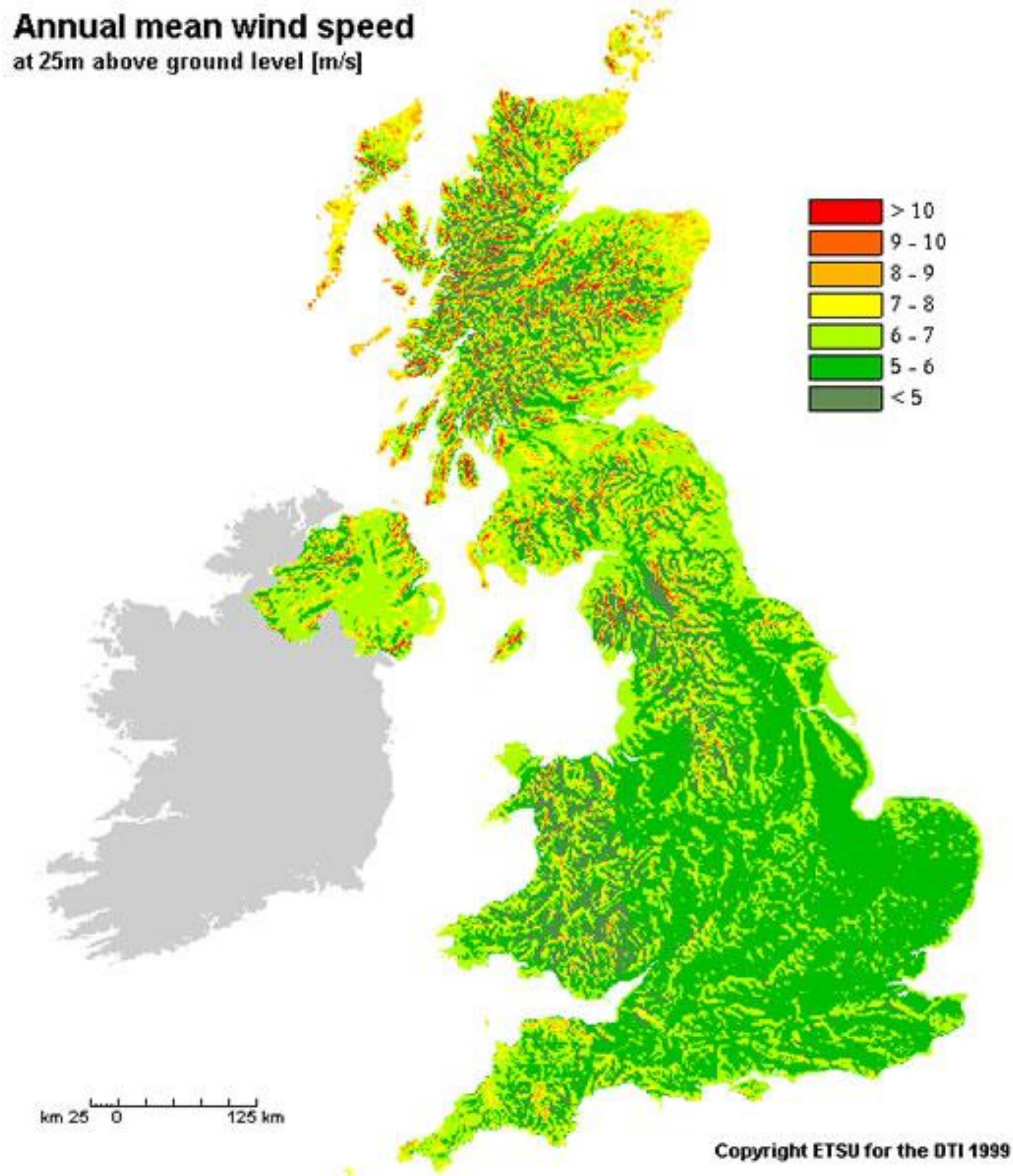


Figure 3.5 – UK wind energy resource

3.1.3 PV

Photovoltaic (PV) panels convert the solar energy (radiation) directly into electricity. When solar radiation (photons) hits the PV cell, electrons (negatively charged particles) are released from the p-n junction (photo diode) substrate that the cell is made from. This release of electrons creates a charge, which, when channelled through metal, conducts throughout the PV cell to produce a direct current (DC). PV panels are usually made up of large arrays of individual cells to give greater power output and minimise the external wiring needed. It is currently one of the most expensive forms of renewable energy, largely because of the cost of silicon, the most common material used. Research and development is currently being undertaken to reduce cost by looking at new and more organic semiconductor materials to replace silicon and also to improve the efficiency of current silicon based designs. As PV panels have no moving parts, they are very reliable and have an expected lifetime of at least 25 years.

The characteristic equation for a generic PV cell is detailed below.

$$I = n_p I_{Ph} - n_p I_{rs}\left[\exp\left(\frac{q}{kTA}\frac{V}{n_s}\right) - 1\right] \qquad \textbf{(3.3)}$$

where $\boldsymbol{n_p}$ and $\boldsymbol{n_s}$ are the number of cells in parallel and series respectively; $\boldsymbol{I_{ph}}$ is the cell photocurrent; $\boldsymbol{I_{rs}}$ is the cell reverse saturation current and $\boldsymbol{V}$ is the cell voltage.
$\boldsymbol{q}$ Electron charge
$\boldsymbol{k}$ Boltzmann constant
$\boldsymbol{A}$ p-n junction ideality factor (1(ideal) - 5 range, usually around 2.4)
$\boldsymbol{T}$ temperature in Kelvin

$\boldsymbol{I_{ph}}$ is directly proportional to solar radiation and the change in temperature.

$$I_{Ph} = \left[I_{scr} + k_i\left(T - T_r\right)\right]\frac{S}{100} \qquad \textbf{(3.4)}$$

$\boldsymbol{I_{scr}}$ cell short circuit current (5A in this case)
$\boldsymbol{k_i}$ short circuit current temperature coefficient (1.5e-3)
$\boldsymbol{T_r}$ cell reference temperature (300K)
$\boldsymbol{S}$ solar radiation in mW/cm^2 (0-100 range)

$\boldsymbol{I_{rs}}$ is proportional to the cell temperature.

$$I_{RS} = I_{rr}\left[\frac{T}{T_r}\right]^3 \exp\left(\frac{qE_G}{kA}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right) \qquad \textbf{(3.5)}$$

$\boldsymbol{I_{rr}}$ Reverse saturation current at T_r (0.7uA)
$\boldsymbol{E_G}$ Band-gap energy of the energy of the semiconductor (1.2eV)

The relationship between voltage and current for various levels of solar radiation is shown in Figure 3.6 for a fixed temperature using equations 3.3, 3.4 and 3.5. As can be seen, there is a constant current as the voltage increases, and then above a certain voltage the current drops away sharply. To obtain maximum power from the PV panel, the operating point needs to hover around the knee of the curve as depicted by the black line in the plot below.

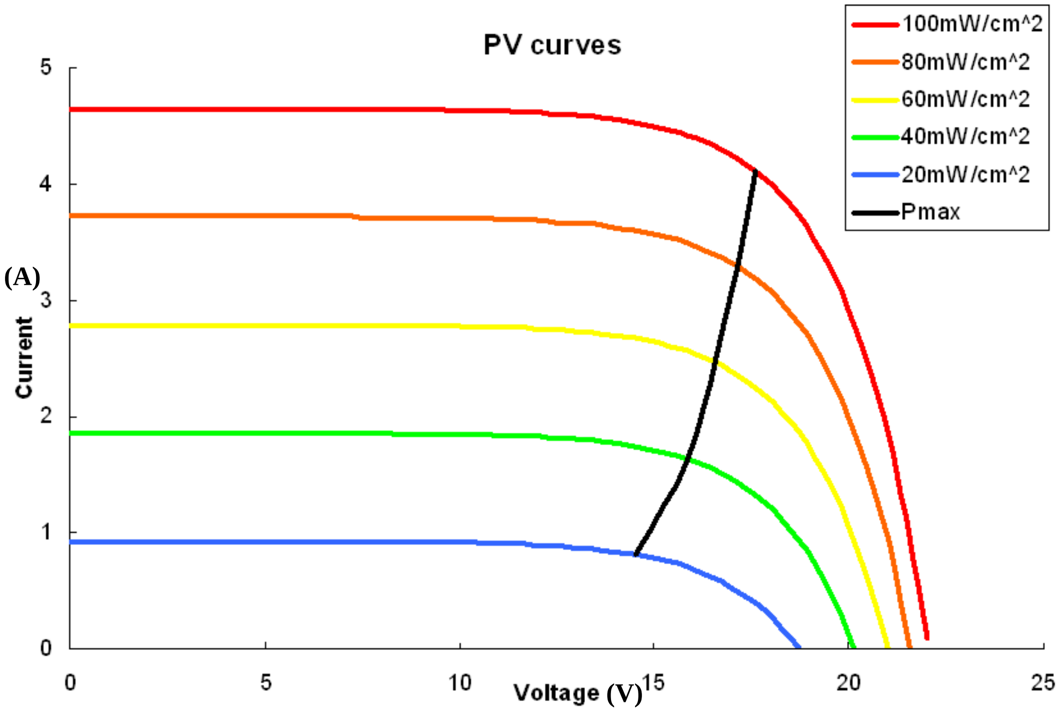


Figure 3.6– PV voltage current curve for various solar radiation levels

3.1.4 Other renewable sources (Hydro, Tidal & Wave)

Although there are other options for renewable power generation, wind turbines and PV are the most mature and accessible technologies currently available.

Small hydro scheme have already been included in some remote hybrid power systems, but as well as being very site specific, they are expensive and normally require a large amount of civil engineering work to be carried out. This is likely to have a greater environmental impact associated with it than other renewable generation. Other renewable resources that may be exploited in the future by island communities in particular are tidal and wave energy. As there is no clear technology winner in either of these fields, they have not been included in this research.

Although these other forms of renewable generation have not been considered, it is expected that they would be able to integrate into the hybrid system given the right form of power conditioning.

3.2 Energy Storage

Energy storage comes in many forms, but is generally defined as "the conversion of electrical energy from a power source into a form in which it can be stored until converted back to electrical energy" [37]. Hybrid systems often need energy storage, because of the inclusion of intermittent renewable generation. In high renewable penetration systems, energy storage is often considered necessary. It helps maximise renewable energy usage by preventing the free energy being dumped, which can be exaggerated by the high minimum loading of diesel gensets. Energy storage can also reduce the frequency of the diesel engine on/off cycling, which has the benefit of reducing engine wear. Another benefit of energy storage is to aid in power system stability during transients.

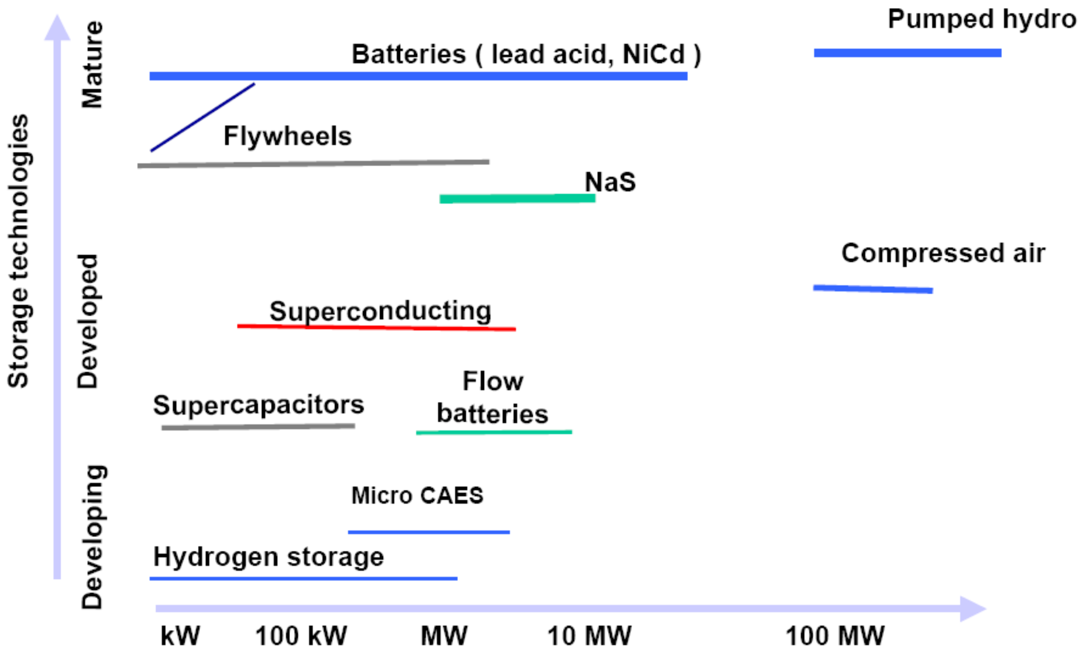


Figure 3.7 - Technical capability and commercial availability of energy storage types [37]

Figure 3.7 illustrates a selection of current energy storage technologies, their power rating range and level of development.

Energy storage can be used for a variety of different roles in a hybrid system. These can generally be broken down into power quality and energy management roles. Figure 3.8 graphically categorizes a selection of energy storage technologies, although some technologies cannot be easily classified, since they are capable of providing both roles (advanced batteries, etc.). Traditionally, lead acid batteries are the most popular form of energy storage found in literature and in use in hybrid systems today.

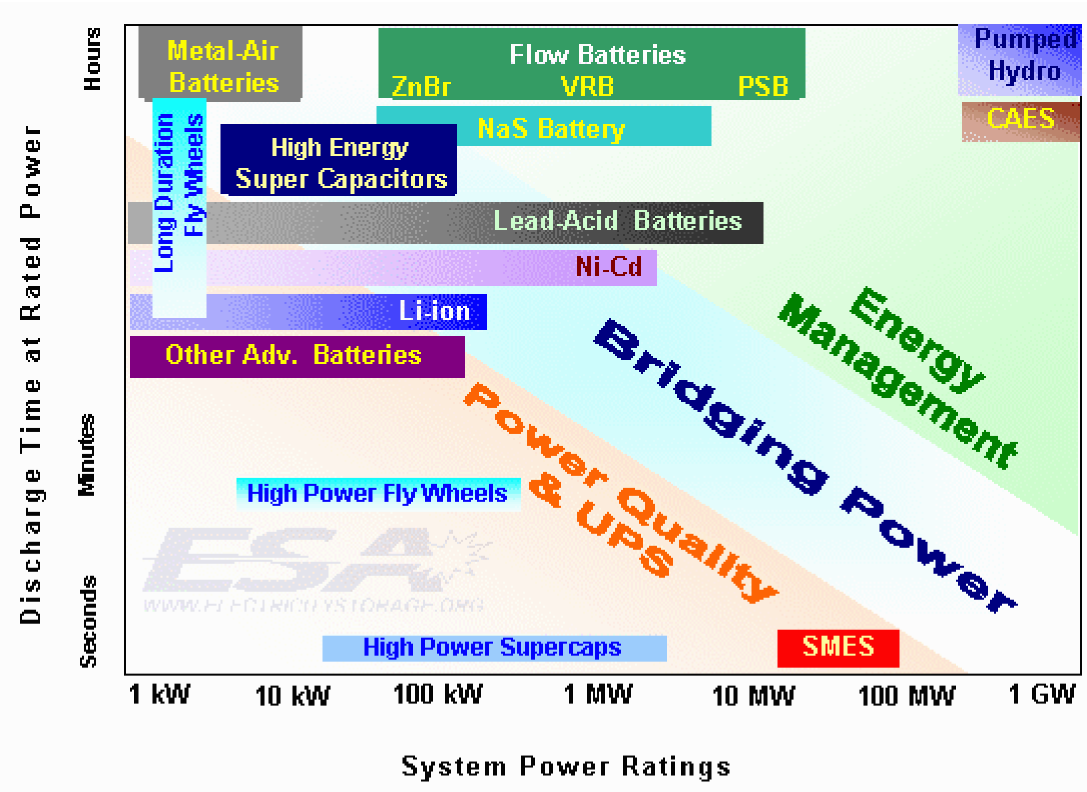


Figure 3.8 – Energy Storage Power and Energy Density [38]

A lot of work is currently being undertaken in the energy storage field. The increasing use of renewable generation has lead to a greater need for higher power and energy ratings for storage to help balance large scale power systems. The increasing interest in electric and hybrid electric vehicles has also spurred research into better batteries and supercapacitors. A list of some of the available options is shown in table 3.2.

System	Life	Efficiency [%]
Pumped Hydro	75 years	70-80
Compressed Air	40 years	70[39]
Flow Batteries	1500-2500 cycles	75-85
Metal-Air	100-200 cycles	50
NAS (Sodium Sulphur)	2000-3000 cycles	89
Other advances batteries	500-1500 cycles	90-95
Lead-Acid	200-300 cycles	75
Flywheels	+15 years	85-95 [40]
Fuel cells	8000 hours [41]	35-50% [42]
Supercapacitors	10,000-100,000 cycles	93-98

Table 3– Energy storage options [43]

3.3 Long term energy storage

Long term or energy management storage technologies allow the time shift of generation, so that it can be used to meet demand. A selection of the suitable options available for use in hybrid systems of the range scale to be studied is examined in this section.

3.3.1 Batteries

Batteries are a mature, reliable and well proven technology, but there are restrictions associated with their use:

1. Temperature limitations
2. Charge & Discharge rates
3. Cost and maintenance

Batteries store energy electrochemically and are one of the most cost effective energy storage devices available exhibiting a high energy density. A Battery Energy Storage System (BESS) is made up of series and parallel connected battery cells to obtain the required energy/voltage levels. Conventional lead-acid batteries have good electrical to electrical turn around efficiencies of 75%. However, they also have a limited lifetime that varies depending on the depth to which they are discharged and the number of charge/discharge cycles. Figure 3.9, shows the relationship between cycle life and depth of discharge.

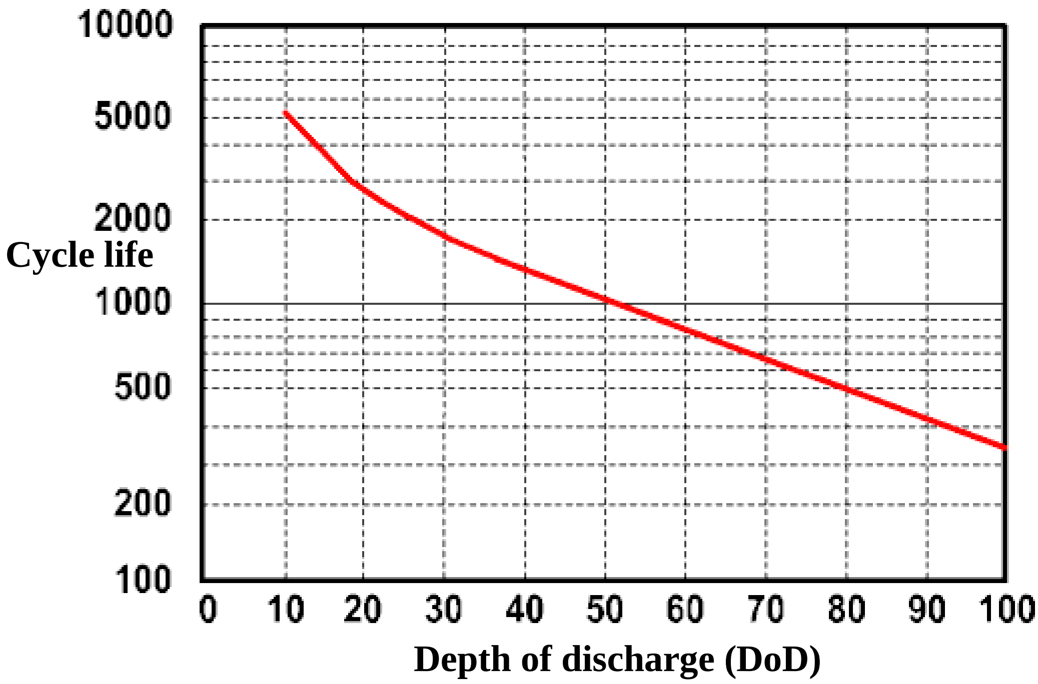


Figure 3.9– Depth of Discharge (%) versus Cycle life [40]

To help prolong BESS lifetime for Valve Regulated Lead-Acid (VRLA), the batteries need to be kept in a temperature controlled environment. This environment may require air conditioning, since the batteries produce large amounts of heat [76] (which is not taken into account in the energy storage efficiency). The condition and charge/discharge of BESS also has to be closely monitored and controlled to ensure maximum performance and lifetime. The State of Charge (SoC), which is the available capacity expressed as a percentage of the batteries rated capacity, needs to be continually monitored, since it is more complicated than simply a measurement of the battery voltage. Due to these factors, BESS normally have their own dedicated Battery Management Systems (BMS).

What is often needed from energy storage in hybrid systems is short periods of high power to minimise start-stop cycles of the diesel engine [8]. Batteries are not ideal for this task due to their inherent current and discharge restrictions, although this can be undertaken to the detriment of the battery life.

High temperature batteries have very high coulombic efficiency, typically 95%, (amp hours divided by amp hour out), but energy is required to maintain their high operating temperature in the region of 300°C [46]. The high temperatures necessitate more stringent thermal management and safety requirements. Materials used in the cell have to be able to handle the higher temperatures and corrosive conditions. Most advanced high temperature batteries have high power and energy densities, but at the moment high production costs are keeping them from being more widely used.

3.3.2 Pumped Hydro

Pumped Hydro storage is in use on the island of Foula in the Shetlands in its hybrid power system [8]. Pumped hydro storage differs from hydropower in that an upper and lower reservoir is required. At times of energy storage need, water is pumped from the lower to the upper reservoir. During times of energy need, the water falls from the upper to the lower reservoir through a turbine generating power. Pumped storage is expensive to build, which is why it is generally only found in areas with natural dams and reservoirs [45]. Even at sites that would naturally lend themselves to pump storage, long design and construction times are likely to occur.

3.3.3 Flow battery

There are a number of different flow batteries currently available, all of which work with the same basic principal of storing the active material outside the battery cell. The electrolytes are then fed into the cell as and when required. This allows the energy storage to be easily altered by changing the electrolyte reservoir size and also means the flow battery power and energy ratings are independent from one another. Flow batteries can be fully discharged and safely left in that state without detrimental effect to the system lifetime. This is in contrast to most batteries, which have a logarithmic relationship between the depth of discharge (DOD) and the cycle life as shown in Figure 3.8. These are high-cost systems and so far only a few demonstration systems have been deployed. Some examples are “Solar house” in Thailand [46], and Kashima-Kita Electric Power Corporation in Japan where a 200kW/800kWh load-levelling demonstration system was installed in 1997 [47]. In 2004, a 250 kW/1 MWh installation was constructed and commissioned by Pinnacle VRB on King Island in Tasmania to provide storage energy for a wind generator for diesel fuel displacement [48].

Technologies	PSB	VRB
C_P (£/kW)	99	281
C_W (£/kWh)	43	66
C_M (£/kW/year)	6	6
Efficiency %	65	70
Lifespan (years)	15	15

Table 4 - Flow battery technical and economic data [49]

C_p power cost
C_w storage cost
C_m maintenance cost
Polysulphide Bromide Battery (PSB)
Vanadium Redox Battery (VRB)

3.3.4 Hydrogen

Hydrogen energy storage has the highest energy density and lowest power density of all the energy storage options discussed. A hydrogen energy storage system consists of an electrolyser, storage tanks and fuel cell. The electrolyser separates water into its component parts of hydrogen and oxygen. In reference [50], it is stated that the electrolyser should have a minimum current limit to ensure hydrogen gas purity. It also declares that electrolysers have a limited cycle life caused by corrosion of the cell membrane with reverse potential on switch off. To overcome these problems, a battery source is introduced into the hybrid system to maintain current and minimise cycling in transient situations. The overall electrical energy conversion efficiency is the poorest of all the systems examined, ranging from as low as 25% [50] to 40-60% in [45]. The electrolyser typically has an efficiency of around 70%, but fuel cells, when used only for electricity production, have an efficiency of only 50%. The process of hydrogen storage has an element of power loss during the compression and transfer of the gas.

Hydrogen technology is currently in a stage of intense development and it is likely that efficiencies, cost and reliability will progress over the next decade and beyond.

3.3.5 Compressed air energy storage

Compressed air energy storage (CAES) systems use an electrical motor driven compressor to pressurise air into a storage tank. Diabatic CAES rejects the heat generated during the compression stage but in adiabatic CAES the heat is captured and stored. Recovering this heat energy helps increase electrical to electrical efficiency, as it can be re-used when the system is generating. The compressed air is reheated using the thermal energy store and then expanded through a sliding pressure air turbine to generate power. Although diabatic CAES is a mature technology, adiabatic CAES is still in the development stage. Two large scale CAES systems are currently in operation; a 290 MW system in Huntorf Germany and a 110 MW McIntosh, Alabama [39].

3.3.6 Energy storage for End Use

There is also the option in many cases for end-use storage, but this may require more complicated control procedures and is similar to load control. End-use storage can take the form of water heating, hydrogen production or water pumping for irrigation. Load control can be highly successful, if end-users are given economic incentives to use the excess power from renewable sources. In practise, there are often correlations between energy production from renewables and energy usage by consumers, for example when it is windy, heaters are often turned up, and when it is sunny, air conditioning is used more.

For fixed speed synchronous wind-diesel generators automatic load control can be applied. This requires no communication between load and generator, as only the frequency of the grid need be known. As the frequency rises, more loads are applied to bring it back down, and vice-versa, for a reduction in frequency. A fuzzy load controller with a random element to switch on and off 15 identical loads is presented in [51]. In a real system, there are likely to be some prioritisation of loads to determine which will be switched off first. Such a system is heavily reliant on end-user co-operation.

3.4 Short term energy storage

Long term energy management energy storage can be used to positive effect in the hybrid power systems under investigation. However, it is not essential, as most forms of renewable generation can be controlled to limit output, or dump loads can be installed to shed surplus power. Economics will ultimately determine which option is used: power shedding or energy storage.

Short term energy storage, on the other hand, is necessary for the correct operation and reliability of the system. Short term energy storage is generally used to aid generators during transients to help maintain hybrid system stability. This is seen as particularly the case in the high penetration hybrid power system using the VSDG in this work.

3.4.1 Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy Storage (SMES) systems have a slightly higher power density and lower energy density than flywheels. High charge/discharge efficiency of over 95% can be achieved [52].

SMES systems store energy by creating a magnetic field through a superconducting coil when a DC current flows through it. The large superconducting coil has to be cooled to cryogenic temperatures (critical temperature of the material being used 4.2K [53]) although high temperature (20-50K [54]) superconductor devices are currently being developed. They can be expensive, compared with other energy storage technologies, due to the cost of cryogenic vessels and refrigeration equipment, but the advent of high temperature devices will help reduce cost. The SMES device can be placed in the DC-link of a back-to-back converter as modelled in [55] for the load levelling of a large 100MW wind farm. SMES devices have fast response capabilities that could make them useful in dynamic and transient conditions, which affect power quality issues.

3.4.2 High power battery

Some of the advanced batteries could see their way into short-term energy storage for power quality due to their high power capabilities. Higher energy densities would also be beneficial in the longer-term energy management of hybrid power systems.

3.4.3 Flywheels

Flywheels use the inertia of a large spinning disc to store kinetic energy. They have a higher power density but lower energy density than batteries. The energy stored depends on the moment of inertia and the square of the rotational velocity as shown in equation 3.6.

$$E = \frac{1}{2} J\omega^2 \tag{3.6}$$

There are two types of flywheel systems used in hybrid systems. In the first example, the flywheel is attached to the shaft of the diesel generator and thus rotates at the same speed as the generator. To allow diesel shut off, a clutch is used to decouple the synchronous generator and flywheel from the diesel engine. Clutches are subject to failure and therefore need periodic replacement. Energy transfer in this case is limited by the acceptable changes in grid frequency.

In the second case, the flywheel is placed separately elsewhere on the system and an electrical machine is used to take or receive power controlled through a power converter. This allows much greater speed variation and hence increases energy availability. Higher rotational speeds are possible, but a vacuum is required to reduce air resistance. Protective containers are required to contain the flywheel in the event of mechanical failure. Tolerances and bearing standards need to be high for high velocity flywheels, which contributes to the high cost. Energy transfer efficiencies for both systems are fairly high at +80% [52].

3.4.4 Super/Ultra Capacitors

The Supercapacitor is an electrochemical double layer capacitor that stores electrical energy by physically separating positive and negative charges. The energy density of Supercapacitors is thousands of times larger than normal electrolytic capacitors. Chemical reactions are not used in operation, which has benefits in terms of cycle life and operational temperature. Supercapacitors can be stored completely discharged, easily installed, are compact in size and can operate effectively in harsh environments (cold, hot & moist). The cost of supercapacitors has been steadily decreasing due to rapid development. Research in to the use of nanomaterials promises to further improve power densities and dramatically improve energy densities. Supercapacitors have a higher power density but lower energy density than SMES. In reference [56], the authors suggest the use of supercapacitors with renewable energy sources, because of their rapid charge and discharge capabilities, unlike batteries. Supercapacitors typically only have a single cell voltage rating of 2.5 Volts. Therefore, they have to be connected in series for higher voltage applications and in parallel to increase energy storage.

One limitation of the supercapacitor when connected in parallel to a DC-bus is that it can only be charged to the upper voltage level and can only be discharged to the allowable lower voltage level, leaving unusable charge on the capacitor [40]. DC/DC converters are able to overcome this limitation but add cost.

Supercapacitors also have a much higher self-discharge rate than batteries, which means they may not suitable for longer-term energy storage. Their long cycle life, operational effectiveness in diverse conditions and high power transfer rates make them a prime candidate for remote hybrid power systems.

3.5 Case Study (Foula)

Foula was chosen as the hybrid system case study due to the depth of information available about the system, community composition and Island population. For simplicity, the power system was chosen to be of a size where only one fully sized generator is needed to supply the load, which ruled out a lot of larger systems. Although these larger systems would benefit from having a VSDG in their multiple generator systems helping supplying any part loads requirements. Keeping the system small also meant the load demand could be simulated at the individual components level. Foula has 17 households and a population of 31 people on the Island.

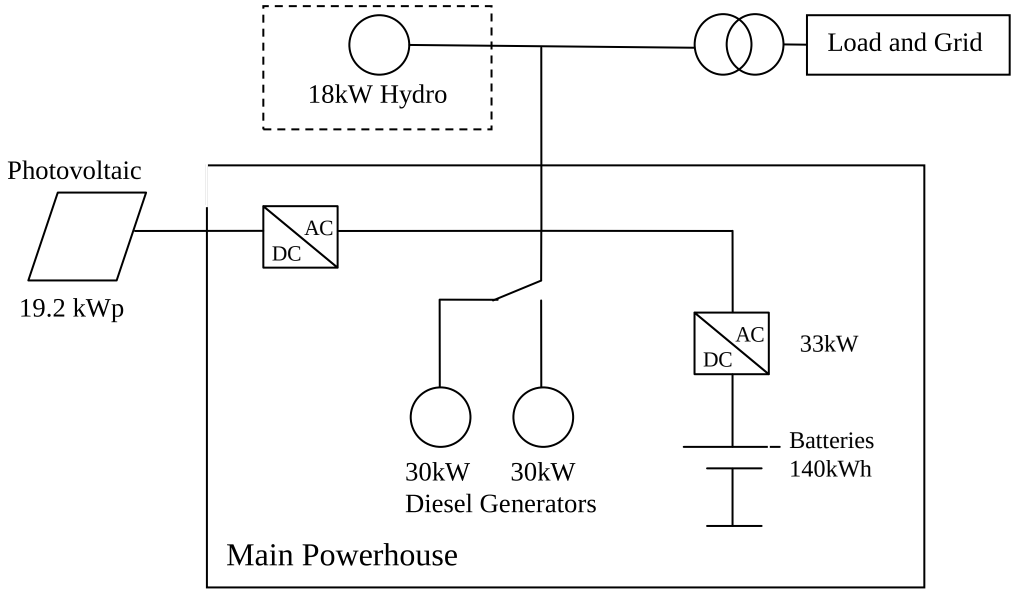


Figure 3.10 – Foula hybrid power system [57]

When Foula's grid operated between 7.20am and 00.30am, the island load would typically vary between 12kW and 22kW. The hybrid power system on Foula as shown in Figure 3.10 now runs 24hrs a day and consists of:

- two 30kW Diesel gensets, although only one can be run at a time
- a 140kWh battery energy system
- a 19.2kWpeak PV array

The battery system has a 33kW bidirectional converter system that is controlled in response to changes in grid frequency. The grid allows loads to be dropped when frequency drops and generation to be shed when frequency rises passed set points by load management switches.

Figure 3.11-3.13 show typical daily load profiles in winter and summer on both weekdays and the weekend. The Island load demand and generation power vary considerably for the days studied. Demand is often around 12kW; if supplied by the 30kW diesel generator alone this would be an inefficient use of the diesel generator. To negate poor part load efficiency, the diesel generator is only run when needed as can be seen from the graphs below. The generator is run when the batteries have reached a set discharge level and renewable generation is insufficient. The generator supplies the demand with any extra capacity being used to recharge the batteries helping keep the diesel generator running at near full load and therefore maximum efficiency.

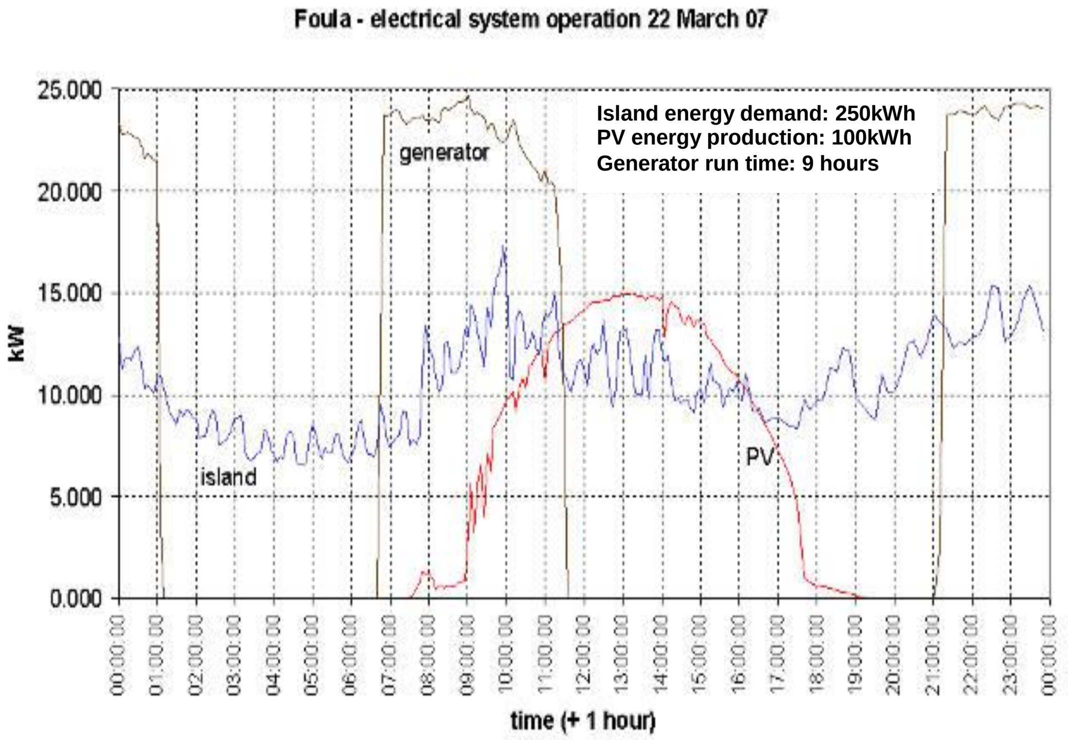


Figure 3.11 – Foula Load and Generation Profile – Tuesday 22nd March 2007 [57]

In Figure 3.11 the load demand (island) and PV and diesel generation are plotted for a weekday in March. No data for the output of the batteries has been available but it is assumed that the BESS meets any shortfall in generation and absorbs any excess. In the early morning, when there is no PV power and demand is still high, the diesel generator is running at a high load both supplying the load and recharging the batteries. Once the batteries are fully charged (01:00) the generator is stopped and the batteries supply the load on their own. By around 06:45 the batteries have become sufficiently discharged to require the generator to supply load and charge the batteries again. During this battery charging period, the PV panels begin supplying power until at 11:30 the PV power is strong enough to supply the entire load. At this point the batteries are suitably charged to back up the PV in supplying the load and the diesel generator is stopped. As can be seen from the plot, soon after this the PV power exceeds the load and the excess PV power is used to further charge the batteries. At 16:30, the PV power drops below the load demand, and the batteries start supplying the load again until they become discharged at 21:00 and the diesel generator starts up.

The PV power for this day is nearly ideal with minimal disturbance throughout the day showing that there was very little cloud cover. The ideal PV daily power profile is a smooth curve from sunrise to sunset, rising to a maximum around midday to 1pm, depending on the time of year. In contrast, the PV power in Figure 3.12 is highly variable, which illustrates that there was a lot of patchy cloud cover that day.

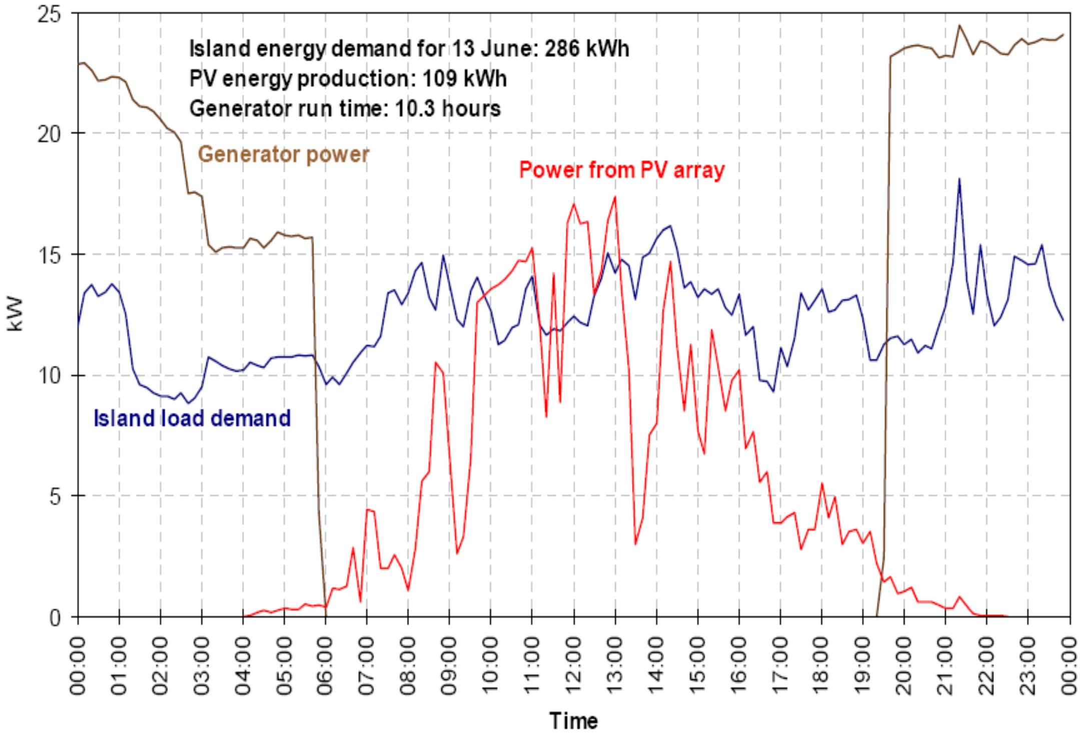


Figure 3.12- Foula Load and Generation Profile – Wednesday 13th June 2007 [58]

The island load demand, PV and diesel generation profile is quite different for the 13th of June as shown in Figure 3.12. The initial diesel generation run, early in the morning ensures that the batteries are fully charged and able to supply the island load alone. PV power fluctuates throughout the day, only supplying the full load and charging the batteries for a few brief periods. By 19:30 the PV panels are only supplying a small fraction of the load demand and the batteries have become drained, necessitating the start up of the diesel generator to supply load and recharge the batteries.

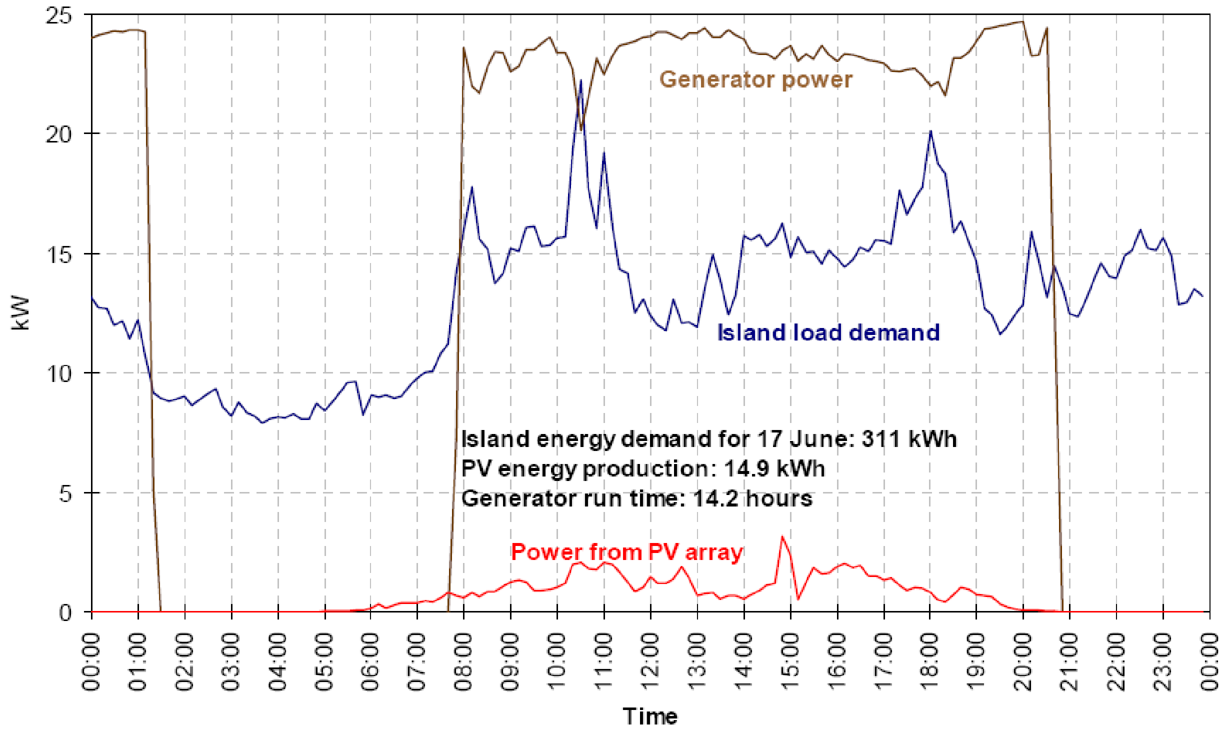


Figure 3.13 - Foula Load and Generation Profile – Sunday 17th June 2007 [58]

On the 17th of June, Figure 3.13, the PV panel produces very little power and so it can be seen that the diesel generator has to run through the middle of the day. It is more than likely that the day was overcast, accounting for the low PV output. Solar resource clearly influences the operation of the complete system.

3.6 Summary

This chapter looks at the reasons for installing a hybrid system, and also different generation and storage options. Several existing systems and their operating schemes are discussed, as well as the different classifications of hybrid system.

The different options for both dispatchable and intermittent generation have been presented. The diesel generator, wind turbine and PV have been chosen as the most suitable technology for consideration in hybrid power system, because of their maturity and ability to be installed at a wide range of sites. The possible energy storage options for both energy management and power quality in the hybrid system have been presented. Only short term energy storage will be further assessed, because this is considered vital to the stable operation of the VSDG.

Finally, a case study hybrid system, Foula, was presented to illustrate the interactions between the dispatchable and intermittent generation.

4 Feasibility Study

The purpose of this research is primarily to reduce the cost of electricity supplied when compared to currently available hybrid wind diesel systems. In this chapter, the possible fuel savings are estimated using a Matlab Simulink model with simplified cost and fuel use calculations. After the fuel consumption and components needed to maintain the VSDG hybrid system power quality had been assessed in more depth, a more detailed assessment of the system feasibility was undertaken. This has been carried out using NREL's (National Renewable Energy Laboratory) HOMER software, an economic optimisation simulation tool for distributed power systems.

4.1 Model to Evaluate Feasibility

Modelling is very useful at the initial stage of any design to determine the feasibility, otherwise high start-up costs would be incurred. Looking at previous work on VSDG, it was evident that for most load cases, apart from near constant full load, fuel savings could be made [10]. What was not evident, was the possible extent of this fuel saving and overall economic viability due to the increased cost of the variable speed generator mentioned in Chapter 2. The effect of the VSDG in a hybrid renewable system also needs to be assessed.

4.1.1 Model Description

The feasibility model comprised of four 15kW wind turbines giving 60kW total maximum power and a single 108kW diesel generator. This hybrid system is considered a high renewable penetration system, as the wind turbines could potentially supply the full load under the right conditions. All systems are presented as black boxes with one input and one output, as shown in Figure 4.1. The individual components will be explained in more detail in this section.

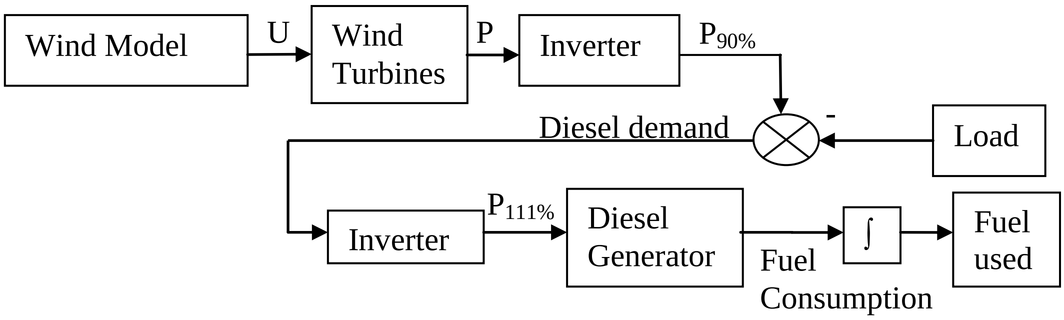


Figure 4.1 – Black box model layout

The wind model is based on the Weibull function (equation 4.4), with mean wind speed and variance being the two main inputs. These are substituted into equation 4.1 from which equations 4.2 and 4.3 can be derived. The Weibull function [8] calculates the probability that the wind is above a certain speed.

$$I = \frac{\sigma}{V_{mean}} \quad \textbf{(4.1)}$$

$$k = I^{-1.086} \quad \textbf{(4.2)}$$

$$C = V_{mean}\left(2.732 + 2.1846I - 1.9361\exp^{I} + 0.1827\exp^{(2I)}\right) \quad \textbf{(4.3)}$$

$$p(V) = \left(\frac{k}{C}\right) \times \left(\frac{V}{C}\right)^{(k-1)} \times \exp^{-\left(\frac{V}{C}\right)^{k}} \quad \textbf{(4.4)}$$

σ variance
V_{mean} mean wind speed, m/s

k shape parameter

C scale parameter

Wind speed data for Skye, a North-West Scottish Island, has been taken from AEA technologies wind speed database and processed using the Weibull probability function [59]. In Figure 4.2, the hours per year based on a mean wind speed of 6.8 ms^{-1} with a variance of 3 ms^{-1} are shown.

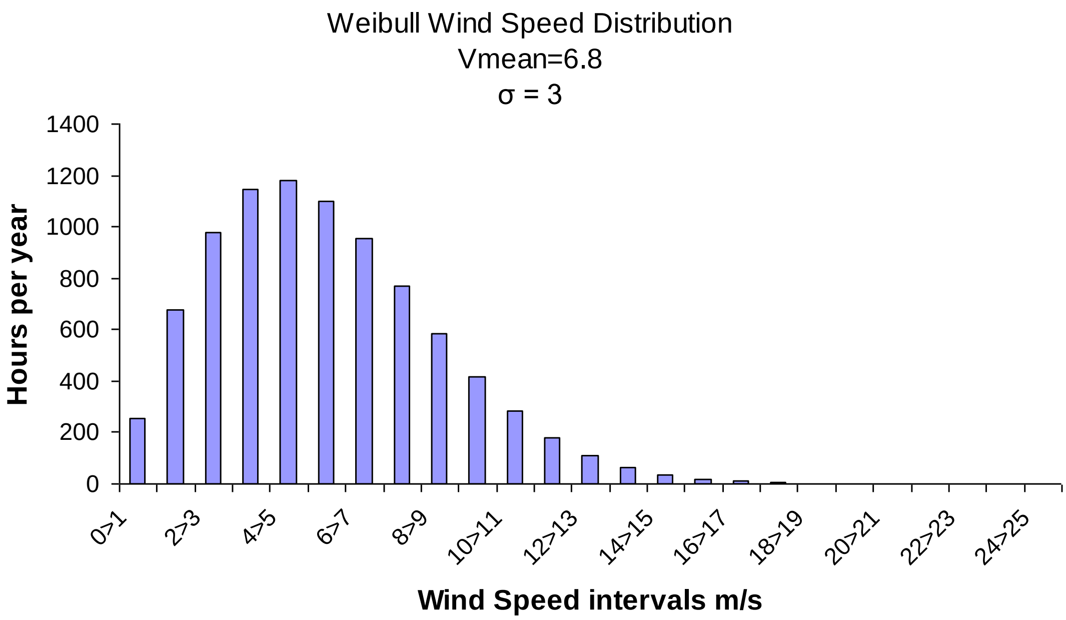


Figure 4.2– Weibull wind speed distribution

The wind speed is then used as the input to a wind speed power curve lookup table based on Figure 4.3 that provides the wind generator output power. This power is then processed through the power electronic converter model, which is a black box with a conversion efficiency of 90%.

The simulated wind turbine model is based on a commercially available Proven 15kW wind turbine [60]. Figure 4.3 shows the DC power curve used in the model. The wind turbine has three 4.5m long glass epoxy downwind rotor blades, which are self-regulating and rotates at 160 rpm at rated output by bending the blades reducing the surface area and aerodynamic efficiency.

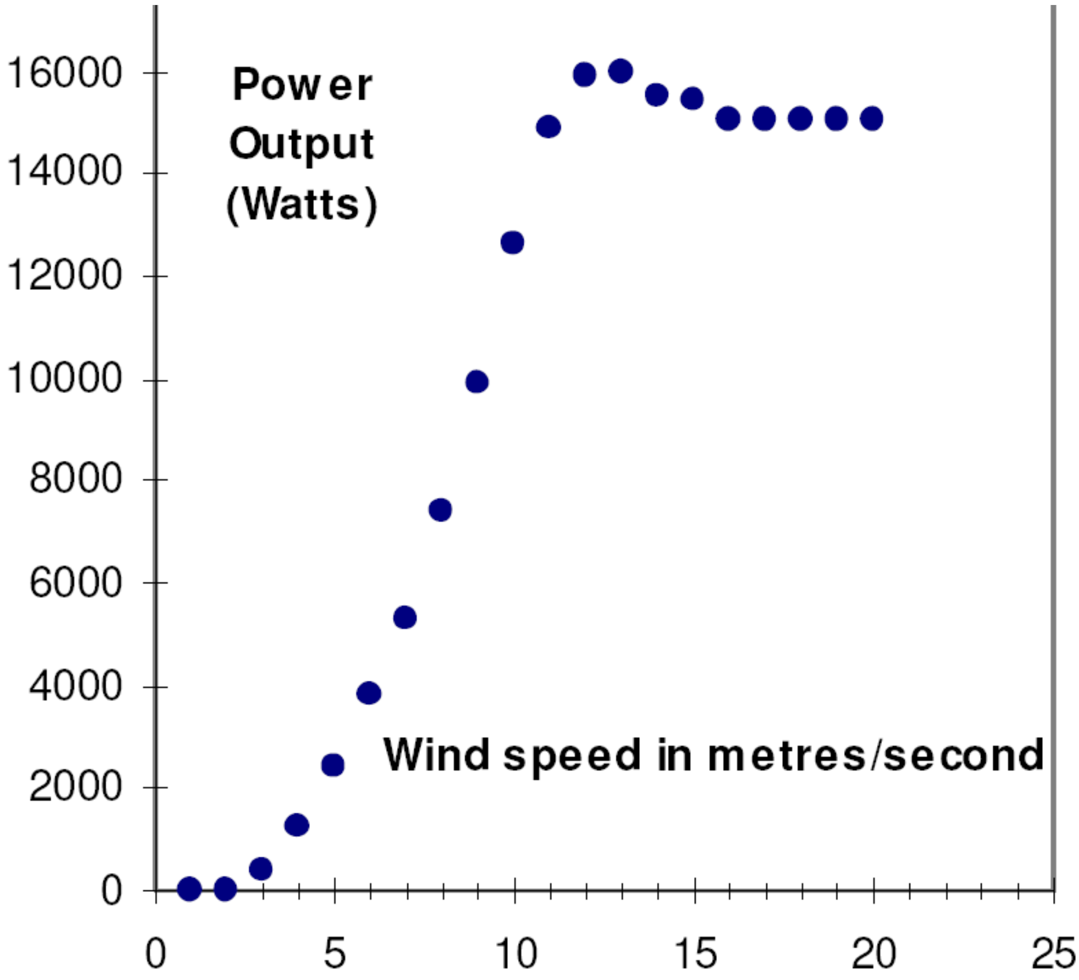


Figure 4.3– 15kW wind turbine, wind speed vs power output curve [60]

In the simulation, the wind turbines are allowed to operate at peak power at all times with any excess power being dumped. In a real system, this dumped energy could be used to heat water or be stored in batteries or any other energy storage device mentioned in Section 3.3. The diesel generator provides any shortfall in load demand not supplied by the wind turbines.

The diesel engine has been modelled on a 108kW turbo charged unit for which engine torque, speed and fuel consumption information was available, as displayed in Figure 4.4 below.

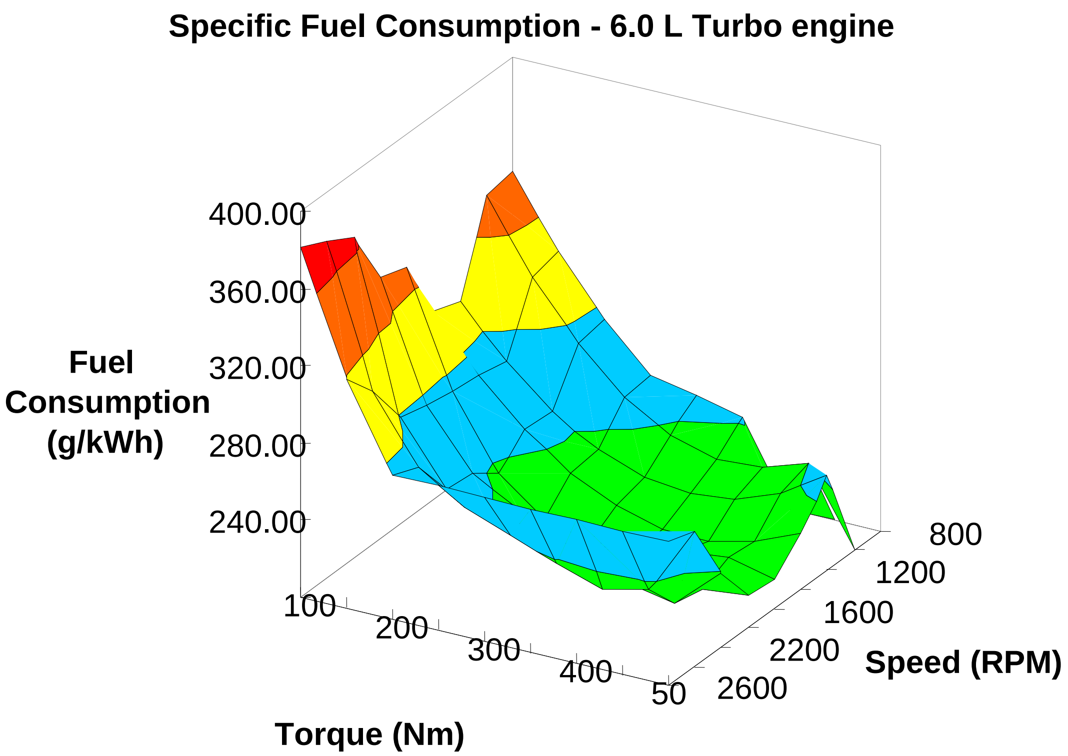


Figure 4.4– 108kW diesel engine specific fuel consumption [77]

Two different models, one modelling a conventional constant speed diesel generator and the other a Variable Speed Diesel Generator (VSDG) have been created from the data in fig 4.4. The fuel consumption power lookup table used for the constant and variable speed diesel generator models is cross-referenced from the speed and torque set points from the data used to create Figure 4.4. Power converter losses are taken into account for the VSDG. As in the same way as with wind turbine, namely a black box with a conversion efficiency of 90%.

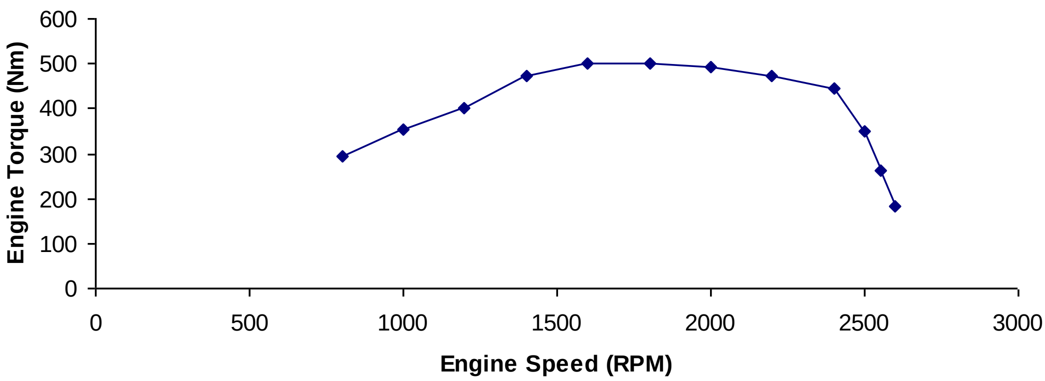


Figure 4.5– Diesel engine Speed Torque curve

Figure 4.5 and 4.6 help illustrate the diesel engine output more clearly than in Figure 4.4. Figure 4.5 is the maximum engine torque across the engine speed range. Figure 4.6 demonstrates the power produced by the engine.

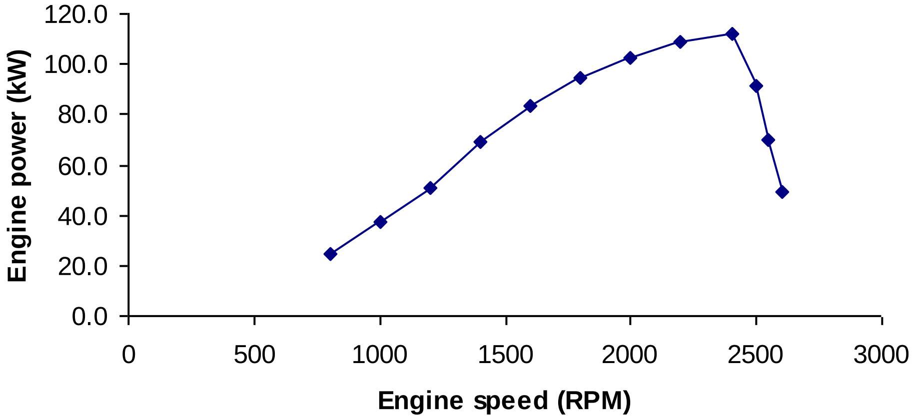


Figure 4.6– Diesel engine Speed Power curve

The fuel consumption for variable and constant speed operation of the diesel generator at different power outputs has been interpreted from the tabulated engine data used to create Figure 4.4 and is displayed in Figure 4.7 below.

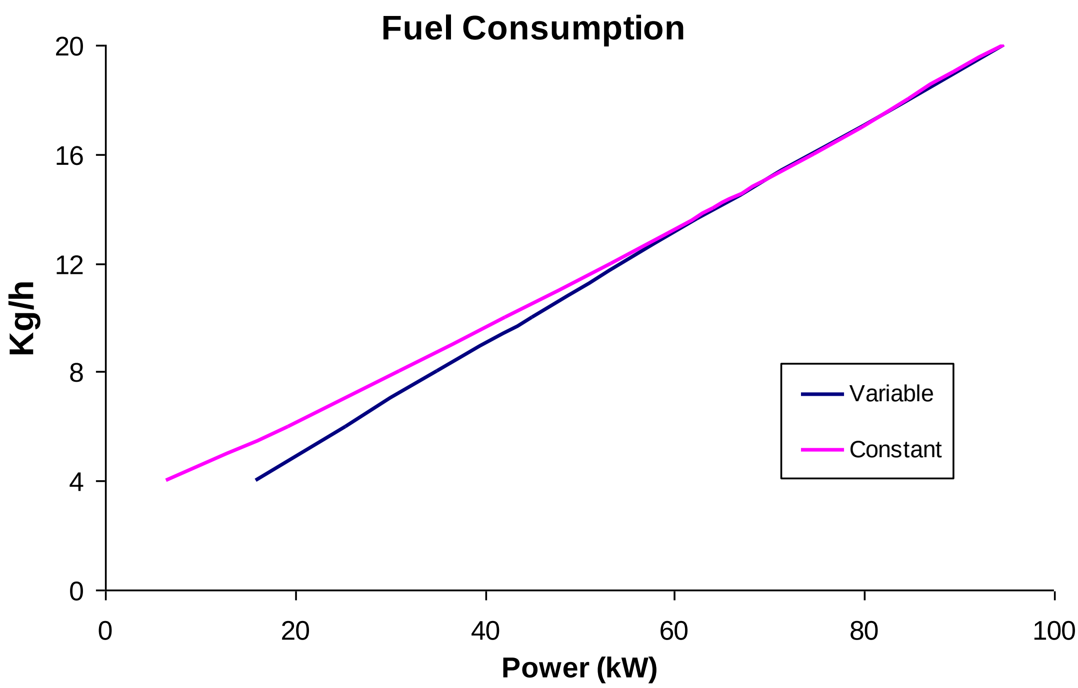


Figure 4.7– Power Fuel consumption curves

As can be seen from Figure 4.7, the margin between the two modes of operation is small in the lower power ranges and non-existent above 65kW.

The turbo diesel engine has been designed for constant speed operation, hence no additional advantage is given to variable speed operation. On the contrary the addition of a turbocharger to the engine will increase fuel consumption during low speed operation because it has been designed to operate at higher rotational speed.

4.1.2 Load

The community load demand is based on that of a typical UK household over 24 hours scaled up to an appropriate size for the diesel generator. The scaled load for the 108kW diesel generator is equivalent to a small community of about 54-72 homes [8] [61]. The load is varied throughout the year to represent the different seasonal demands, increasing for cold and windy winters for example. Figure 4.8 displays a typical load profile for a summer day.

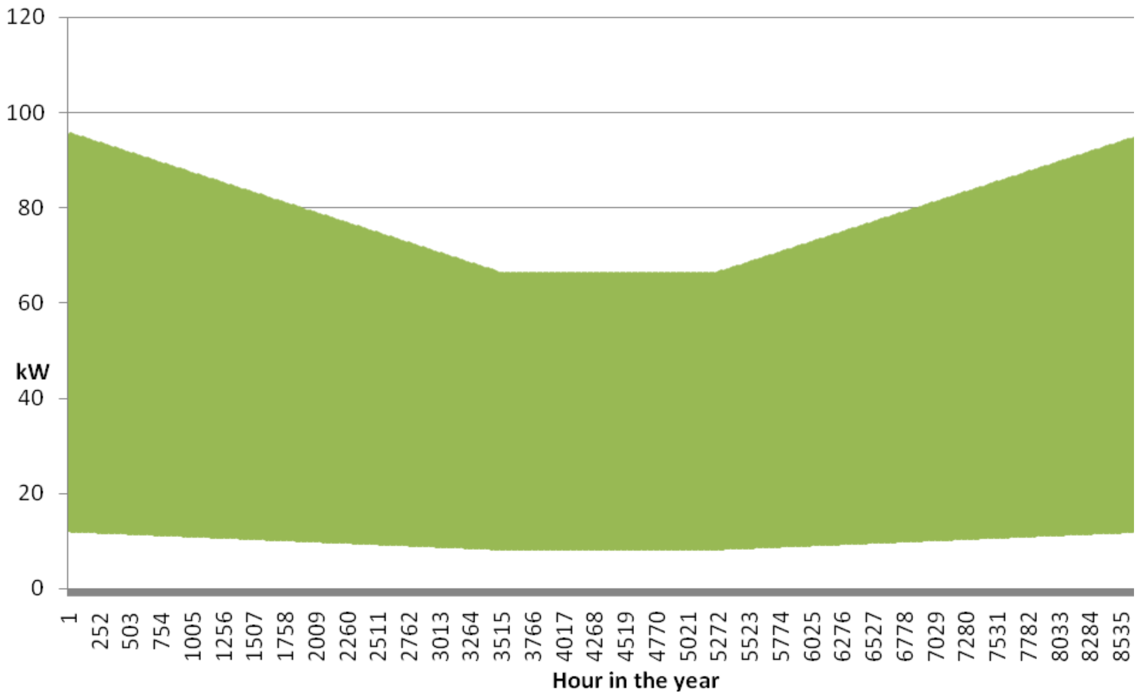


Figure 4.8– UK household summer load profile [8]

4.1.3 Results

Simulations of the constant speed diesel generator and VSDG on their own and in hybrid systems with wind turbines have been carried out for one complete year. During this time, the load supplied to the community was some 376,000 kWh, which was calculated by integrating the load power and dividing this by the time period in hours. In the hybrid systems, the wind turbines supply around a third of the energy needed although 10% of the generated energy is dumped, as shown in Table 4.1, due to wind power overproduction.

LOAD	WIND	DUMPED
376 000	126 800	12 700

Table 5– Energy in kWh

The fuel used by the diesel generator for 4 different power system models is shown in Table 4.2 below. The first two models compare the different modes of diesel generator operation on their own. The Diesel model uses a constant speed diesel generator to supply the load. The VSDG model uses a variable speed diesel generator to supply the load. The hybrid models simulate the two different modes of diesel generator operation in a hybrid wind diesel system. The Wind/Diesel model implements a wind turbine and constant speed diesel generator hybrid system. The Wind/VSDG model uses a variable speed wind turbine and diesel generator hybrid system.

Fuel	Constant Speed Diesel	VSDG	Wind /Constant Speed Diesel	Wind/VSDG
Kg	94 800	84 680	77 070	63 140
Litres	111 529	99 623	90 670	74 282
£	55 765	49 812	45 335	37141

Table 6 – Fuel use and cost comparison
(Density of Diesel 0.85kg per litre, Diesel fuel at 50p per litre)

The following observations can be made from the data in Table 4.2:

- In the diesel generator only case, variable speed operation saves 10,120 kg (or 11%) of diesel fuel per annum over constant speed operation.

- The addition of the wind turbines produces an 18.7% fuel saving for the constant speed diesel generator and a 25.4% saving for the VSDG.
- Looking at only the hybrid systems, variable speed operation saves 13,930 kg (or 18% of 77,070kWh) of diesel fuel per annum over constant speed operation.
- The savings incurred in running a variable speed hybrid system over the constant speed stand-alone diesel generator are 31,660 kg (or 33% of 97,800kWh) of diesel fuel per annum.

The main cost of running a diesel generator comes from the fuel costs, and so the degree of savings should provide a good financial incentive.

An economic evaluation was carried out using a low price of 50 pence per litre for agricultural diesel[2]. The possible annual fuel saving of the variable speed hybrid system simulated compared with the standard diesel genset is £18,624, from Table 4.2. The cost of four 15kW wind turbines, including masts and rectification converters, is around £100,000[3] and are likely to reach payback at 8-10 years. Given a 20-year lifetime, the savings should be in the order of £300,000.

The VSDG will have a substantial premium compared with a standard diesel generator, because of the need for a fully rated converter, and so any anticipated savings need to be considerable. The combination of the VSDG with wind turbines should ensure low diesel loading and hence low fuel consumption for prolonged periods. Although the VSDG will cost more than a conventional diesel generator, the anticipated hybrid system should not, because the inverters, which are estimated to cost about £5000 per wind turbine, have been omitted from the above calculation as the hybrid system is to be fully integrated sharing the DC link and an inverter. It has therefore initially been shown that the VSDG in a typical community load cases,

[2] Diesel price obtained from CPL Petroleum 11/08/05 for the Isle of Skye

[3] Proven 15kW wind turbines; Generator £15,000, Isolation + rectification £500, Mast(height dependant) £8-15,000

where nominal load is generally low compared to peak (generator sizing) load, should be financially viable both on its own and in a hybrid system.

4.2 Economic Analysis

HOMER is an optimisation and sensitivity analysis model used in the evaluation and design of both off-grid and grid-connected micro power systems. It enables many different technologies, system configurations and capacities to be compared quickly and easily under a variety of defined sensitivity variables. Examples of sensitivity variables are fuel costs, wind speed and interest rates, but in general can be any value that is not fixed. Simulations are normally run over long time periods (lifetime of system) with energy balance calculations carried out for every hour of operation.

The user provides all required information about the system which includes;

- Component purchase, replacement and maintenance cost
- Component lifetime (hours or years)
- Component performance (fuel consumption load curves, wind speed power output curves etc)
- Number and size of components to be considered
- Renewable resource
- Fuel costs
- Economic inputs (interest, project lifetime etc)
- Loads
- Energy storage

Other possible inputs include System Control

- Determining battery/energy storage dispatch
- Generator(s) operation/scheduling
- Deferrable loads (dump loads etc)),

Emissions

- Costs/penalties
- Limits (discarding systems that exceed them)
- Constraints (maximum annual capacity shortage, operating reserve, stopping infeasible system appearing in the results)

Homer uses these inputs and compares all possible combinations, producing results sorted by net present cost detailing all lifetime or simulation period run information such as fuel use, cost of electricity, renewable energy fraction, diesel run time etc.

The Net Present Cost (NPC) is calculated according to the following equation [62]:

$$C_{NCP} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \qquad \textbf{(4.5)}$$

where:

$C_{ann,tot}$= total annualised cost [£/yr]

$CRF()$= capital recovery factor

i= interest rate [%]

R_{proj}= project lifetime [yr]

HOMER ranks systems by total NPC, not by the cost of energy.

The annual real interest rate is related to the nominal interest rate and annual inflation rate by the equation given below.

$$i = \frac{i^{'} - f}{1 + f} \qquad \textbf{(4.6)}$$

where:

i = real interest rate (%)

i'= nominal interest rate (% rate at which you could get a loan)

f= annual inflation rate (%)

For example, if the nominal interest rate is 5% and the inflation rate is 3%, the annual real interest rate is 1.94% (as %, not general number 5%-3%/(1+3%) = 0.02/1.03).

The annual real interest rate, therefore, factors out inflation for the economic analysis. It is assumed that the rate of inflation is the same for all costs.

The capital recovery factor is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The present value is the equivalent value at the present of a set of future sums, taking into account the time value of money.

The equation for the capital recovery factor is:

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad \textbf{(4.7)}$$

where:

i = interest rate

N= number of years

Example: for i = 7% and N = 5 years, the capital recovery factor is equal to 0.2439. A £1000 loan at 7% interest could therefore be paid back with 5 annual payments of £243.90. The present value of the five annual payments of £243.90 is £1000.

4.2.1 Homer Model Description

The modelled hybrid power system consists of a diesel generator, load and a choice of between zero and three wind turbines. No energy storage has been included in the model, although excess electricity has been produced.

The wind turbine is based on a generic 20kW unit available in HOMER, with a 15m hub height although wind turbine details and the power curve can be easily changed. The capital cost for one unit is £25000 and the wind turbine has a 15 year lifetime with replacement costs of £20000.

Item	**Unit**	**Cost**
Wind turbine	20kW (0 to 3 units simulated)	£25,000 (£20,000 replacement after 15 years)
Wind speed	6.4, 7.58 & 8.5 m/s	Weibull shape factor of 2
Diesel	100kW	Table 8 (30,000 hours overhaul)
Load	750, 800, 850 & 894 kWh/day	0.393 load factor
Diesel fuel	50, 60 & 70p/litre	
Real interest rates	5, 7.5 & 10%	

Table 7 – Case details

The wind resource has been entered in monthly averages although hourly data file imports are possible. The annual mean wind speed is 7.58m/s at an anemometer height of 10 meters with a Weibull shape parameter K value of 2. The variation of wind speed with height, displayed in Figure 4.9, has been calculated using a surface roughness length of 0.03m equivalent to that of a fallow field [60].

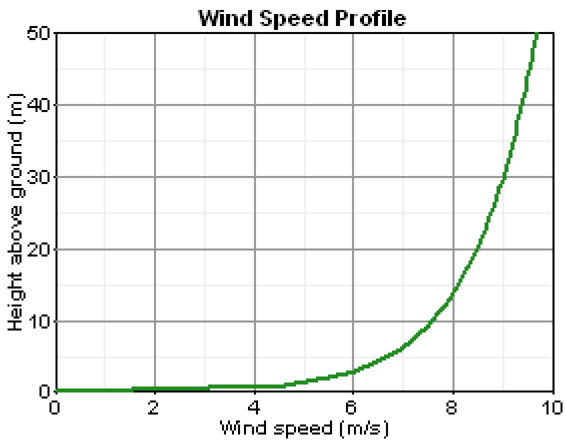


Figure 4.9 – Wind Speed with height variation

The mean wind speed at 10m height has been given three sensitivity values of 6.4, 7.58 and 8.5 m/s. The different values have been chosen to demonstrate the impact wind speed has on the energy produced by the wind turbine.

The diesel generator model has four different variations to take into account: constant speed and three variable speed units as shown in Table 4.3. The variable speed diesel generators differ in their minimum run speed, which requires different levels of supercapacitor power boost, which is why they have different capital costs.

Genset	Capital	Overhaul [78]	Min Load kW	$L/hr/kW_{output}$	$L/hr/kW_{rated}$
Constant	£11500	£10000	40	0.216	0.035
VS 1800rpm	£25300	£10000	20	0.237	0.019
VS 1400rpm	£29900	£10000	15	0.245	0.012
VS 1000rpm	£34500	£10000	10	0.246	0.011

Table 8– Diesel Generator stats

The last two columns of table 4.3 display the parameters used by HOMER to define the diesel generator fuel consumption. $L/hr/kW_{rated}$ is the no load fuel consumption of the diesel generator divided by the rated output, and $L/hr/kW_{output}$ is the extra fuel consumption needed to supply the load.

The premium paid for the variable speed wind hybrid system over the constant speed wind hybrid system will be less than shown above, because of integration of power electronic converter between wind and diesel, such that there is only one grid side inverter. In the maintenance costs, it has been assumed that only the diesel engine will require maintenance, and hence the cost is the same. The overhaul cost is representative of the cost of a new diesel engine after the 30,000 hrs operational life. The VSDG overhaul has been estimated to be the same as that of the constant speed diesel generator, as the supercapacitors and power electronic converter should last for the lifetime of the system. The lifetime of the system differs, with the VSDG having an increased lifetime due to their reduced running speed.

Diesel fuel has been given three sensitivity values of 50, 60 and 70p/L (with 50p/L being around average in April 2008).

The primary load has been given a daily load pattern (in one hour periods) for each month of the year although hourly data files can be imported. The resulting annual average load is 894 kWh/day (326,310kWh/year) with an annual peak of 94.8kW and a load factor of 0.393. Three percent daily and hourly noise has also been added to the load, which represents the individual appliance usage better than the constant load for each hour.

The load has been given four sensitivity values of 750, 800, 850 and 894 kWh/d.

The project has a 15 year lifetime with annual real interest rates of 5, 7.5 and 10%. No other system controls or constraints have been added and the controlled generation simply follows the demand.

4.2.2 Results

For the 8 simulations and 432 sensitivities, the most economic option in all cases is where the most expensive VSDG with the lowest minimum run speed and therefore least possible fuel use.

Table 4.4 below lists the most economic option for each diesel generator variation for the base case of 894kWh/day load, 7.58m/s mean wind speed, £0.5/L diesel fuel and 5% interest rate . The NPC and Cost of Electricity (COE) give an economic comparison of the best options available.

Genset	No. Wind Turbines	Initial Capital	Total NPC	COE (£/kWh)	Renew Fraction	Diesel (L/yr)
Constant	1	£36,500	£647,063	0.191	0.17	103,835
VS 1800rpm	2	£75,300	£561.402	0.166	0.34	79,851
VS 1400rpm	3	£104,900	£515,974	0.152	0.47	65,393
VS 1000rpm	3	£109,500	£491,896	0.145	0.5	59,867

Table 9 - Diesel Generator comparison

The wind turbines have a capacity factor of 38.6% (30% is considered good in the UK for larger wind turbines). Average annual turbine output is 7.73kW with 7,894 operating hours per year giving a total of 61,020kWh. Average annual diesel generator output is 23.4kW and the maximum load is 90.9kW with operational life lasting three and a half years (30,000hrs) after which the diesel generator is overhauled.

The yearly emissions for the hybrid system with three wind turbines and variable speed diesel generator are compared to that of a variable speed diesel generator only system in Table 4.5.

Pollutant	Emissions Hybrid (kg)	Emissions Diesel only (kg)
Carbon dioxide	157,649	236,634
Carbon monoxide	389	584
Unburned hydrocarbons	43.1	64.7
Particulate matter	29.3	44
Sulphur dioxide	317	475
Nitrogen oxides	3,472	5,212

Table 10 – Emissions comparison

The results have been shown to be to a certain degree relatively insensitive to mean wind speed, diesel price (assuming it will only increase) and interest rates with the variable speed (1000rpm minimum) hybrid always producing the cheapest electricity. The load, and more specifically the load factor, has the greatest impact on the results. The load factor is defined as the average load divided by the peak load. If the load factor is increased from 0.393 to 0.703 some sensitivity combinations result in the constant speed generator having the cheapest electricity.

This only occurs with combinations of some of the most extreme cases, for example low mean wind speed (5m/s), minimum diesel fuel cost (£0.5/L) and very high real interest rates (10%).

Mean wind speeds as low as 5m/s are on the threshold of viability for wind turbines when replacing mainland grid electricity. This also has the effect of increasing the average diesel generator load, which reduces the benefits of variable speed operation. At high speeds and high loads, the variable speed generator starts to resemble constant speed operation, but the additional losses from the power electronic converters further increase fuel consumption.

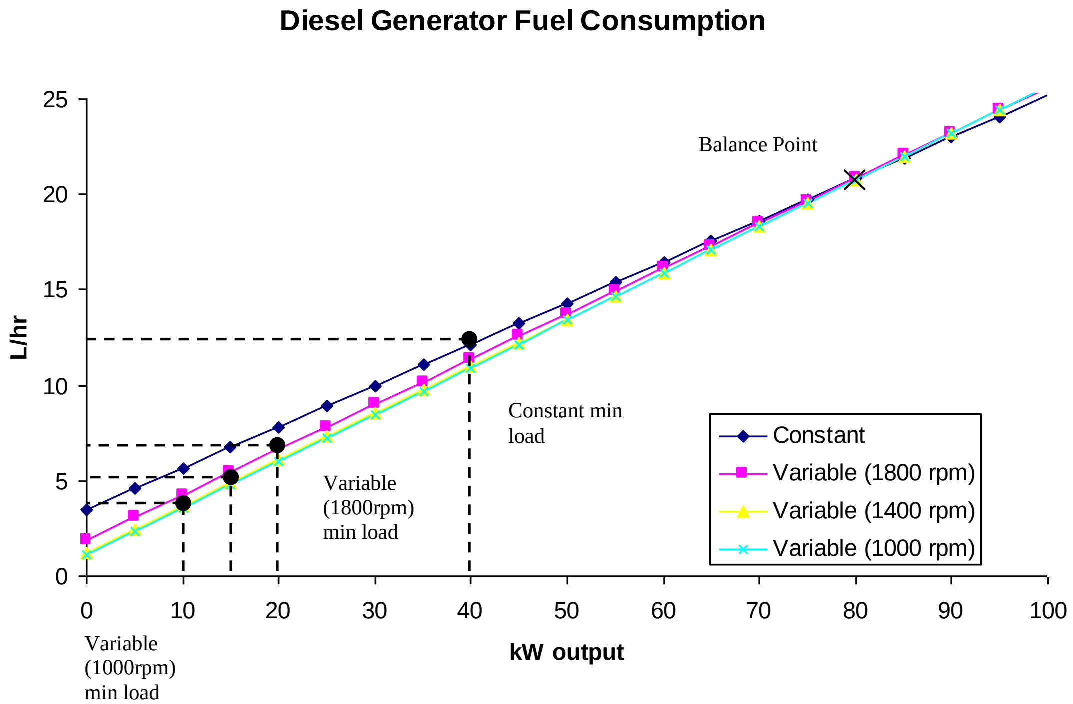


Figure 4.10 – Fuel Consumption Power Curve

In the fuel consumption graph, Figure 4.10, it can be seen that the balance point between constant and variable speed fuel consumption is around 75kW (or 75% of maximum) for the diesel genset used in the hybrid simulations. Below this point, to about 50kW the fuel saving of the variable speed generator is negligible (under 0.9 L/hr or 8%) and it is unlikely to offer total overall lifetime cost savings. However, this can be affected by generator lifetime, as the longer the lifetime, the less per year capital cost of the generator. Generator lifetime can in turn be affected by many aspects, including daily operating hours, maintenance, environment, load variability and vibrations caused by harmonics, and fuel and air quality.

The breakdown of average power supplied by the generators[4] in each month of the year (for the high load factor case) is illustrated below in Figures 4.11-14 for different wind speeds and has been tabulated in Table 4.6 for one years operation.

[4] Wind is the combined wind turbine power (3 × 20kW) and Generator 1 is the 1000rpm VSDG

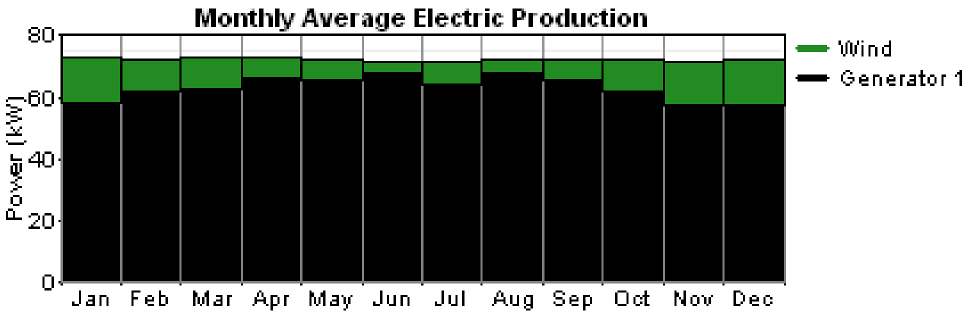


Figure 4.11- For 5 m/s

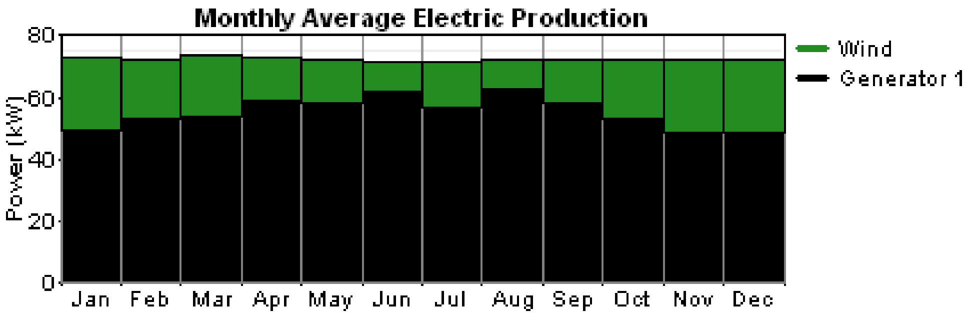


Figure 4.12- For 6.5 m/s

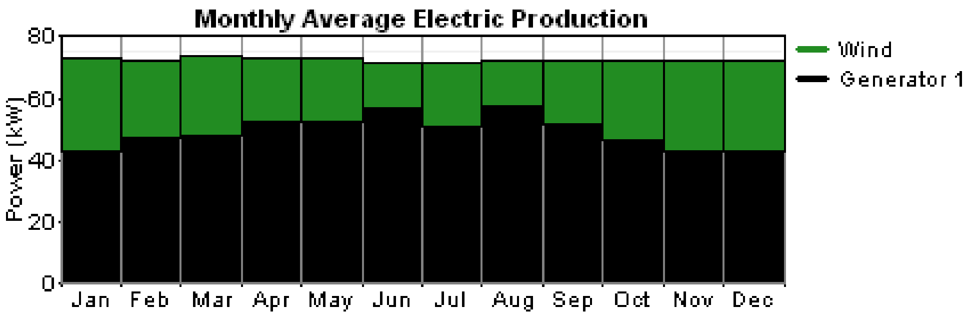


Figure 4.13- For 7.58 m/s

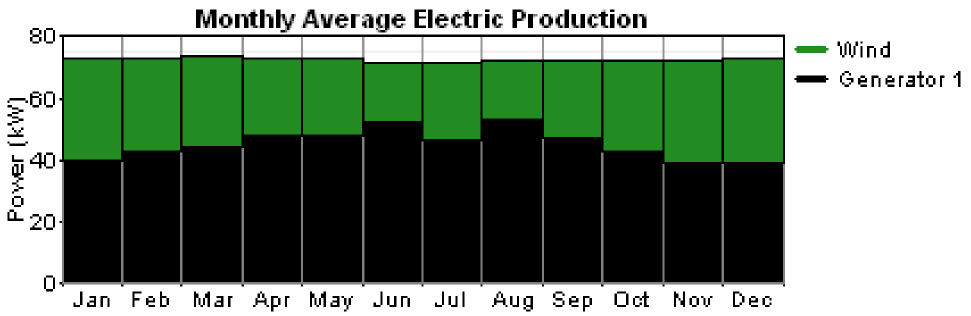


Figure 4.14- For 8.5 m/s

Mean Wind Speed (m/s)	Average output for 3×20kW Wind Turbine (kW)	Average Diesel Generator Load (kW)
5	9.14	63.1
6.4	17	55.4
7.54	23.2	49.4
8.5	27.2	45.4

Table 11 – Generator annual average production

Diesel fuel cost is only likely to increase from the current value, as demand increases from developing countries and oil extraction becomes more difficult and therefore more expensive. The diesel fuel price of £0.5/L will probably already be surpassed by the time of submission of this thesis, if it has not already, and as this price increases, so will the transportation cost for many of the remote communities that depend on diesel generator powered grids.

4.3 Summary

The VSDG system was first shown to be financially appealing due to the possible annual fuel savings, both as a standalone generator and as part of a wind diesel hybrid system.

A more detailed cost analysis was then carried out using the HOMER simulation software for the lifetime of the system. The VSDG was again shown to have very strong fuel and total life time cost savings. Not only would this reduce fuel costs, but also fuel storage and transportation costs. The VSDG has been given a very high capital cost of three times a normal constant speed genset, because of the use of supercapacitors for power quality/system stability, power electronics and a permanent magnet generator. The overall capital cost of a hybrid system would be reduced by the shared use of the power electronic inverter with the wind turbines. Nevertheless, the VSDG still produces the most economic hybrid system for a wide variety of sensitivities. Only for high load factor systems, where the VSDG would not have originally been considered, the constant speed diesel generator provides cheaper electricity.

In conclusion, simulation results of the VSDG in a hybrid system have been shown to reduce fuel use by 19-50% with total lifetime costs 11-34% less than for a constant speed wind diesel system.

5 Modelling & Simulation

In order to better understand the basic operation and performance of the advanced hybrid power system, simulation models have been created. Using computer simulation helps reduce development cost and time during the initial optimisation and for simulating the system over a long time scale.

In this Chapter, the performance of the hybrid power system over a variety of different time scales will be investigated. Table 5.1 outlines the three major simulation types of interest in general power system studies. Models have been created for each of the simulations types.

Simulation Type	Detail	Representation	Time Step	Time frame	Typical Problem
Electro-magnetic Transient	Down to electronic power converter switching	Differential equations	10Hz-kHz Microseconds	>Seconds	Power Electronic converter behaviour
Power System Dynamic	Only fundamental frequency components	Load Flow equations	0.1-10Hz Milliseconds	Seconds to Minutes	Voltage Stability
Power Balance	Power Sources	One input one output black box models.	<10Hz Seconds	Tens of Seconds to Days	Maintaining power balance, Financial

Table 12– Power system simulation type [63] [64]

In [65] its stated that only the subsystems that determine the behaviour in the frequency range of interest should be included.

The sub transient model, modelling down to individual switching events, will be used to study the behaviour of the power electronic system and its control. This model will be looking for any possible unwanted interaction between the different generators connected through DC/DC converters to the common DC-link.

The Power System dynamics model of the hybrid system uses a reduced detail model focusing on device power control to determine the power flow equations. The power system dynamic model has been used to study the operational performance of the system in maintaining the DC-link voltage.

The Power Balance model uses a slightly reduced detail model of the Power System dynamics model, but with the time step interval increased to 1 minute in line with the available data time series period. The power balance model examines the long-term power balance performance and the use of resources to estimate running costs.

The modelling and simulation work has mainly been carried out in Matlab Simulink. Matlab is a high level programming language that can be used to quickly solve iterations of mathematical equations. Simulink is a GUI for Matlab helping model dynamic systems and links building blocks that contain Matlab code to achieve this. It is a more user-friendly way of creating models than Matlab and enables quick alteration to the model values and design. The use of block diagrams enables one to visualise the processes and interaction within the model more clearly.

5.1 Electromagnetic transient model

Now that the variable speed hybrid system has been shown in Chapter 4 to be worth pursuing economically, further investigation of the operational performance is needed. Detailed models of the hybrid system components have been created to enable the transient performance of the individual components and interactions to be evaluated.

The complete electrical and electronic side of the generators and converters have been modelled for the sub transient simulation. This simulates down to individual switching events in the inverter and DC/DC converters (in the kHz range). Figure 5.2 shows the VSDG model broken down into its main parts: engine, generator, rectifier, DC/DC converter, inverter and 3 phase load.

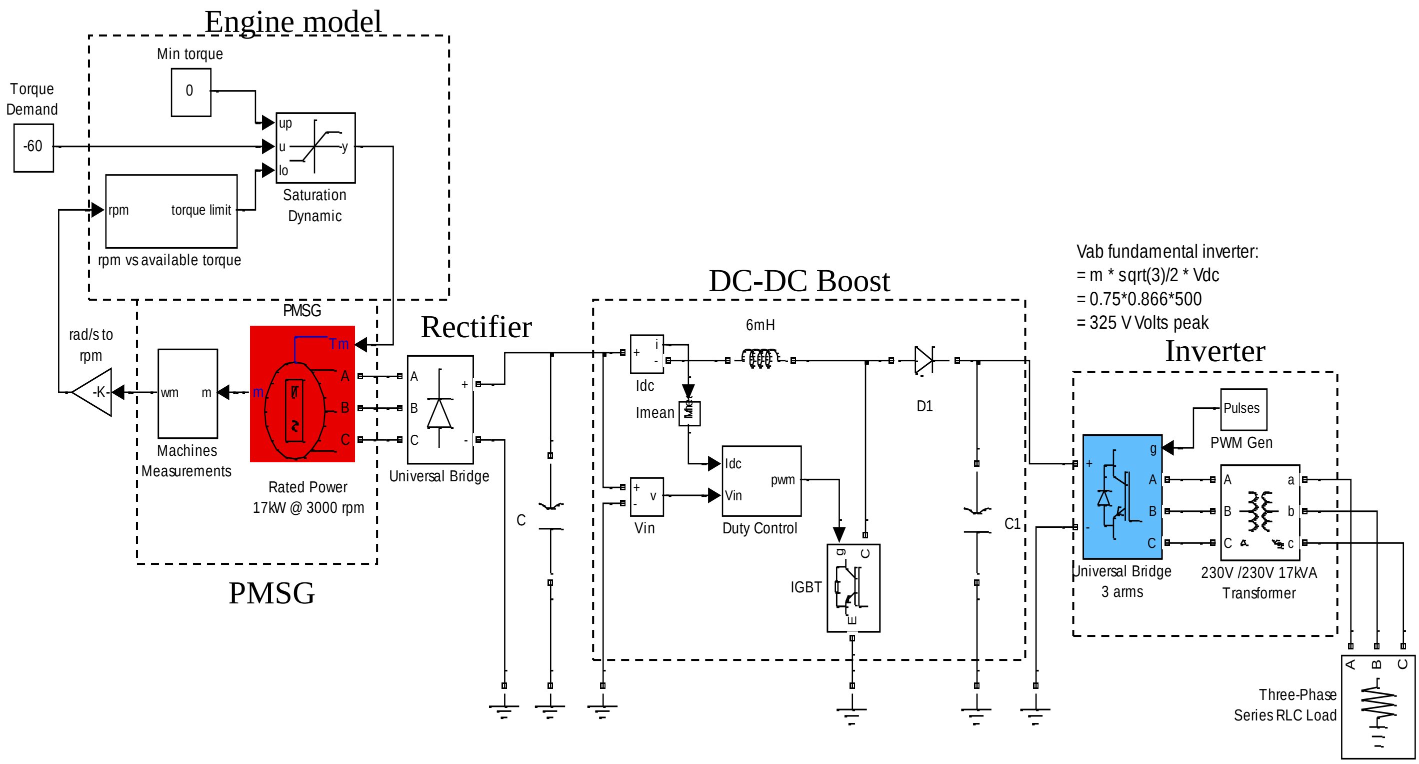


Figure 5.1– VSDG sub transient model

The electrical side of both the wind turbine and VSDG have the same form comprising of PMSG, Diode Rectifier, DC-DC boost converter and Inverter. The PMSG has a torque input, the wind turbines torque value is dependant on wind and rotor speed and for the diesel engine the available torque is a function of engine speed.

A similar model for the wind turbine has been created and the two models combined at the DC-link, illustrated in Figure 5.3.

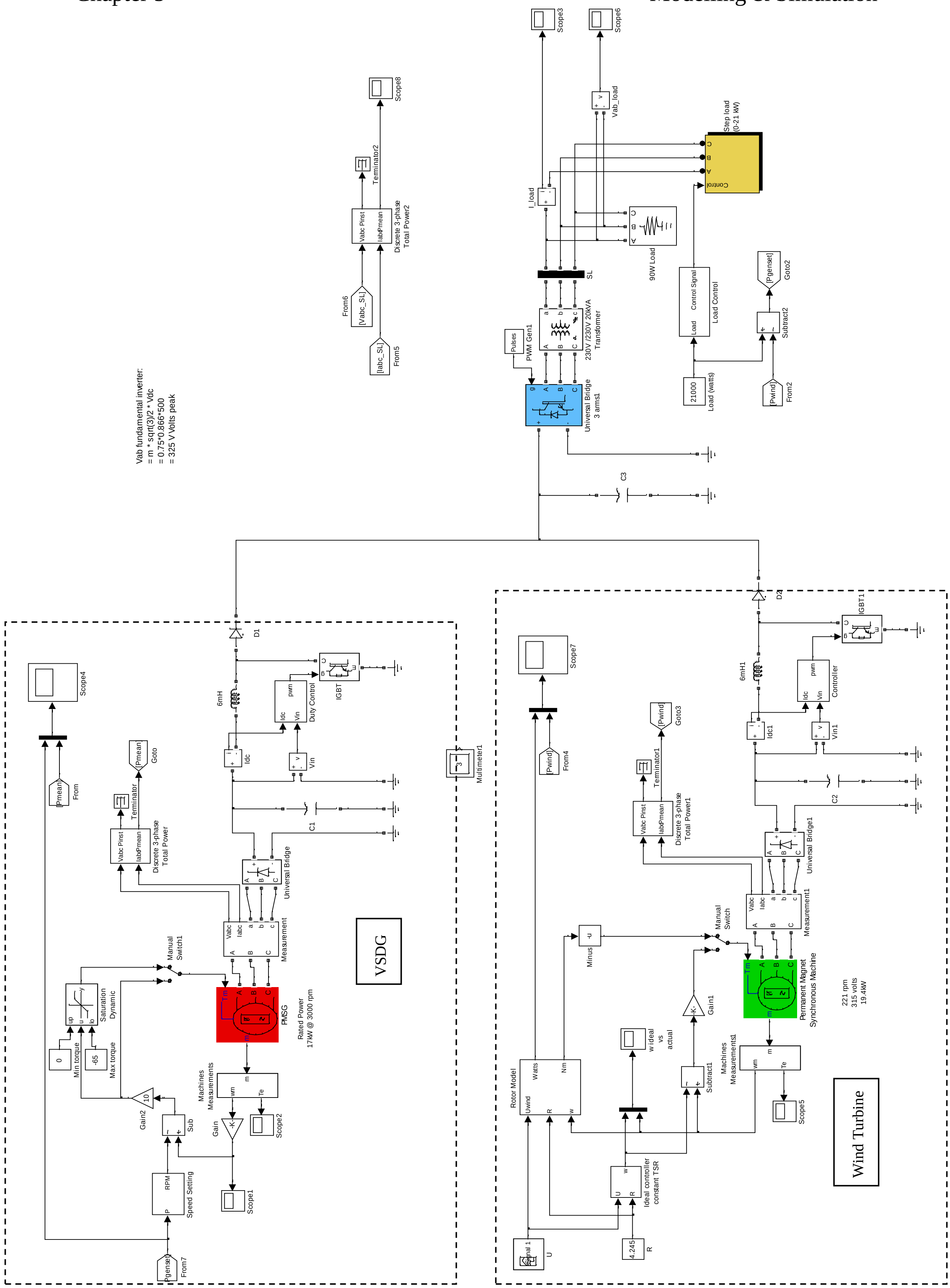


Figure 5.2 – Hybrid system sub transient model (dclinkhybrid2)

The block diagram below breaks down the model into the main components and shows how they are connected up. The red lines and text show the generator control signals and the black lines indicate electrical connections.

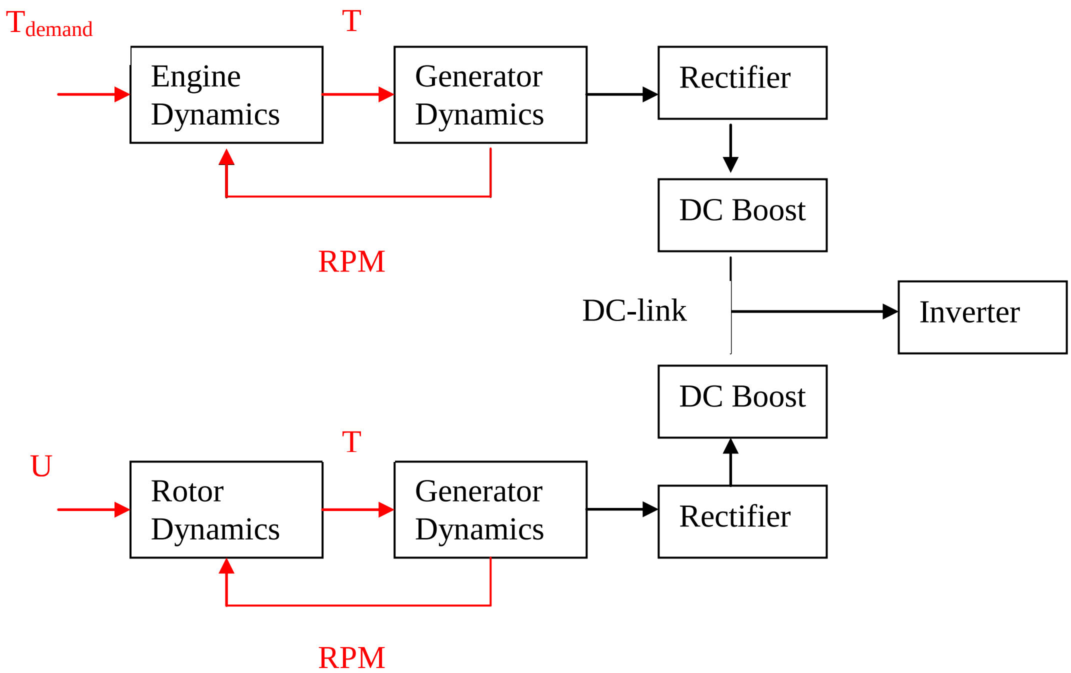


Figure 5.3 – Hybrid system sub transient model block diagram

The variable frequency variable voltage AC power that is produced by the generators is converted by the diode rectifier into a varying voltage DC source. The DC voltage ripple is reduced by a capacitor. This variable DC voltage is boosted to a constant DC voltage across another stabilising capacitor. A three-phase inverter samples this constant voltage to create grid voltage and frequency supply. A transformer is then used to filter out the switching frequencies of the inverter.

The frequency of the sine wave is user specified and its amplitude is dependent on the modulation index, m. The magnitude of the modulation index, m, depends on the level of DC voltage input that has to be let through, according to the equation 5.1.

$$V_{ab} = m \times \sqrt{\frac{3}{2}} \times V_{dc}$$

$$= 0.75 \times 0.866 \times 500$$

$$= 325\ Volts\ peak \qquad (5.1)$$

These more detailed models helped validate the intended operating method of the DC/DC converter for the common DC-link voltage control in the hybrid wind diesel system. The high level of detail and hence reduced step time of these simulations meant long run times, and therefore they were only useful for very short simulation times.

Figure 5.5 illustrates the correct operation of the hybrid system. In this test, the wind turbine power is reduced because of the 11 to 9 m/s wind speed drop, while the VSDG maintains power balance in the DC link. Any change in the DC-link voltage would be projected on to the inverter AC voltage output, but as can be seen this is not the case as the sine wave amplitude remains consistent.

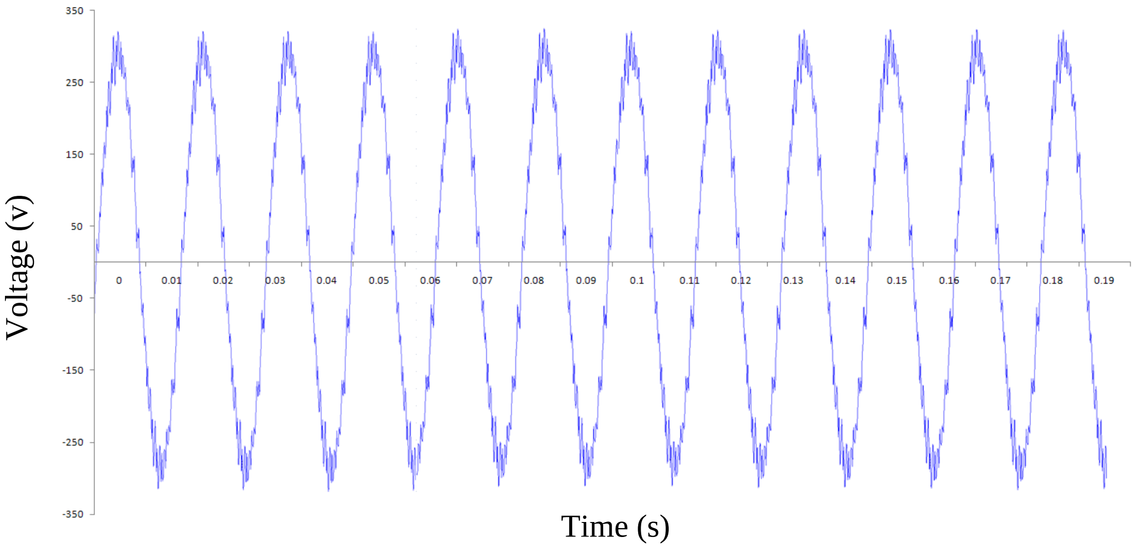


Figure 5.4 – Electromagnetic transient model inverter output

5.2 Power System Dynamics

The hybrid system Simulink model, shown in Figure 5.6 below, includes detailed electrical machine modelling using the Simulink SimPowerSystems machines block sets. The different generator models are electrically isolated and are only linked by the power produced, highlighted by the green P_{wind} signal routing. The diesel generator and wind turbine model are similar to the models found later in this section but have Permanent Magnet synchronous generator (PMSG) blocks instead of equations of motion for the generator dynamics, and thus both electrical and mechanical characteristic are included.

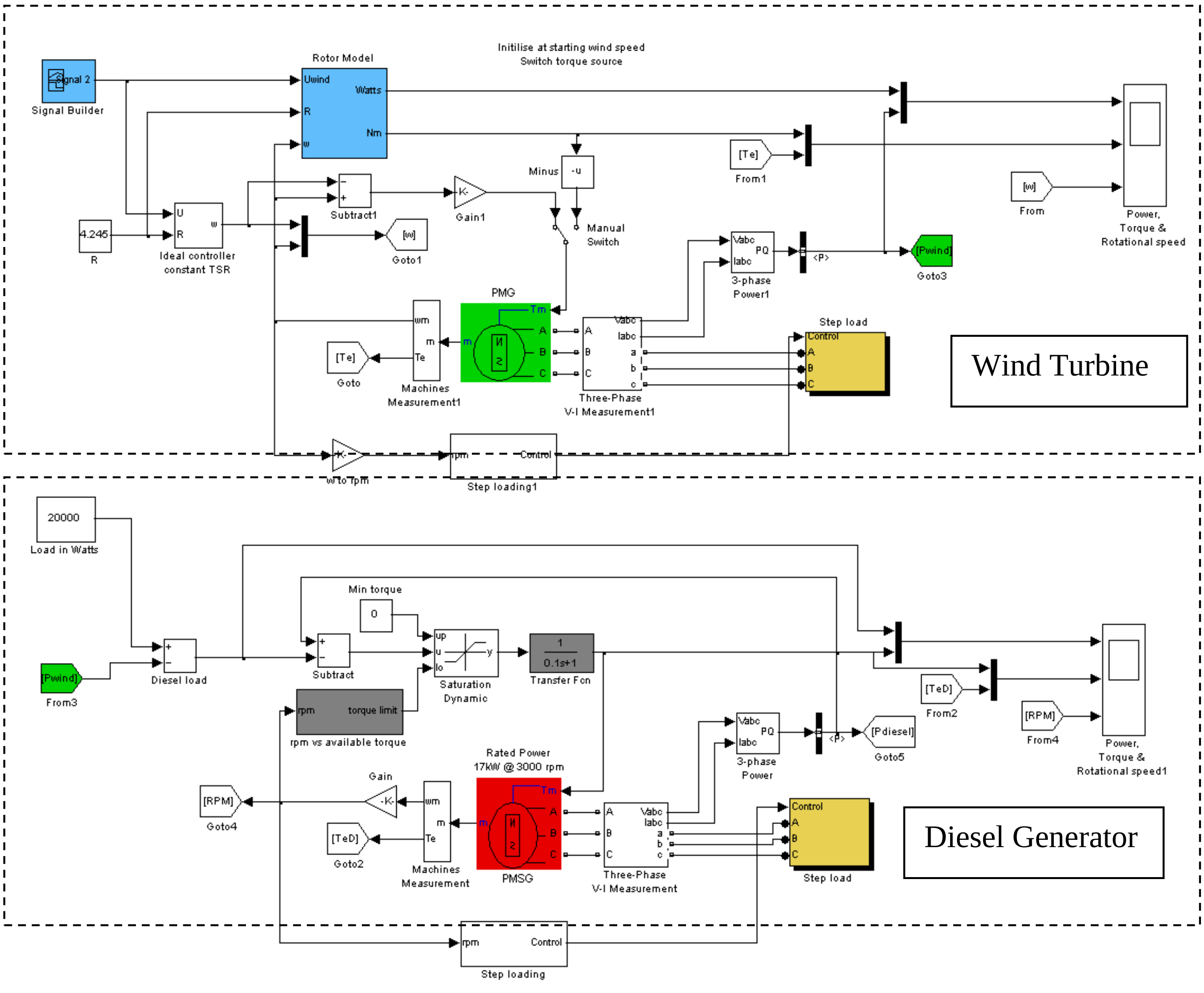


Figure 5.5 – SimPowerSystems Power system dynamic model

The Permanent Magnet synchronous generator template from the SimPowerSystems toolbox has been used with generator parameter information for the wind turbine coming from [66] for a 20kW machine and from [14] for a 17kW diesel generator.

The generator parameter input data for the wind turbine and diesel generator are listed below in table 5.2.

Parameter	20kW Wind Turbine	17kW diesel generator
Nominal Speed (rpm)	211	3000
Pairs of poles	36	12
Frequency out	126.6 Hz	600 Hz
Resistance (ohms)	0.1764	0.195
Inductance (Ld(H), Lq(H))	4.48mH, 4,48mH	300µH, 300µH
Moment of Inertia (kg·m2)	30	0.22
Flux Density (wb)	0.4	0.175

Table 13 – Permanent Magnet synchronous machine parameter inputs [66], [14]

A test was carried out to assess the variable speed generators ability to match the constant load under drops in wind speed.

Below is a graph showing the hybrid system behaviour to three wind speed drops:

- 11-9 ms^{-1} in one second at 1.8 seconds
- 9-6 ms^{-1} in one second at 6 seconds
- 6-3 ms^{-1} in one second at 11 seconds

The graph clearly shows the power deficits in the system when the wind speed suddenly drops. During the 9-6 ms^{-1} wind speed drop the undelivered power peaks at around 5kW, which is a very sizable portion of the 20kW load, the other wind speed changes do not bring about as large a shortfall (VSDG has more available power for the first drop, and power drop in the last wind speed drop is smaller). Key parameters affecting the stability of the system are wind turbine inertia and diesel engine torque as would be expected.

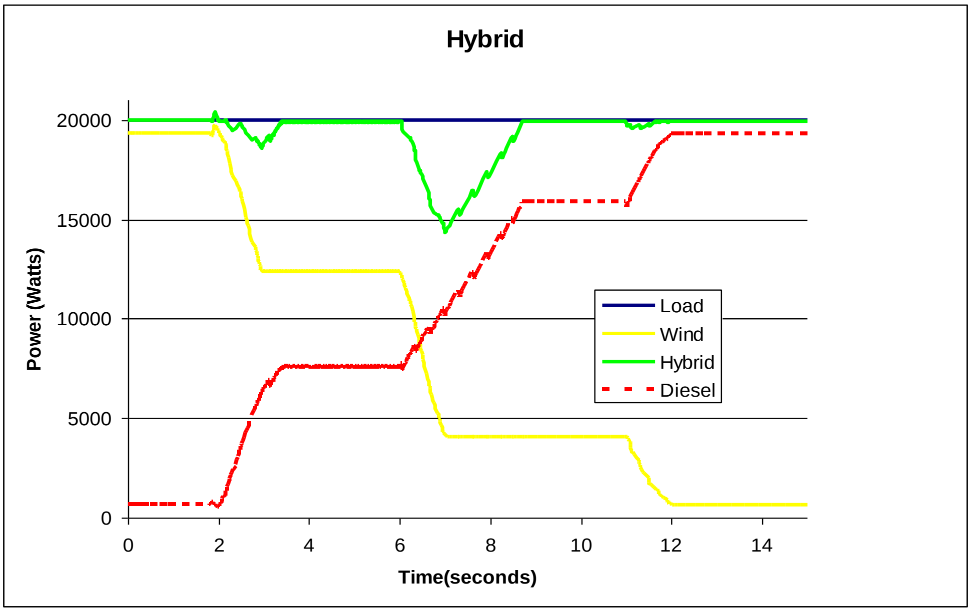


Figure 5.6 - SimPowerSystems Power system dynamic model results to wind drops

In [63] it is stated that the generator and converter can be modelled as a torque source, as any torque set point can be instantaneously reached by injecting the appropriate rotor or stator currents. Therefore, it is not necessary to include the generator equations and the only remaining differential equations are the equations of motion. In [67], it is said that the variable speed wind turbine can be described as an active and reactive power source that are functions of average wind speed and only the details of the control system need to be modelled.

Can the same be assumed for PMSG since there is no direct control over the stator currents with an uncontrolled rectifier? The PMSG VSWT previously modelled does have a torque control in the form of the DC-boost control, so in theory it should behave the same. For the VSDG the inverter can control the torque of the generator.

In [68] it is noted that the torque-current characteristics of the PMG are independent of speed and bus voltage, therefore torque current relationship is constant.

5.2.1 Constant Speed Diesel Genset

The model for the constant speed diesel Genset is similar to that of the VSDG shown in Figure 5.8, with the omission of power converter losses and a speed controller optimised for constant speed operation.

5.2.2 VSDG

The VSDG model is detailed in Figure 5.8 and consists of four main parts, the equations of motion (Generator Dynamics), Engine dynamics (Engine model), Generator setting (electrical torque limitation) and the control (torque and speed controllers).

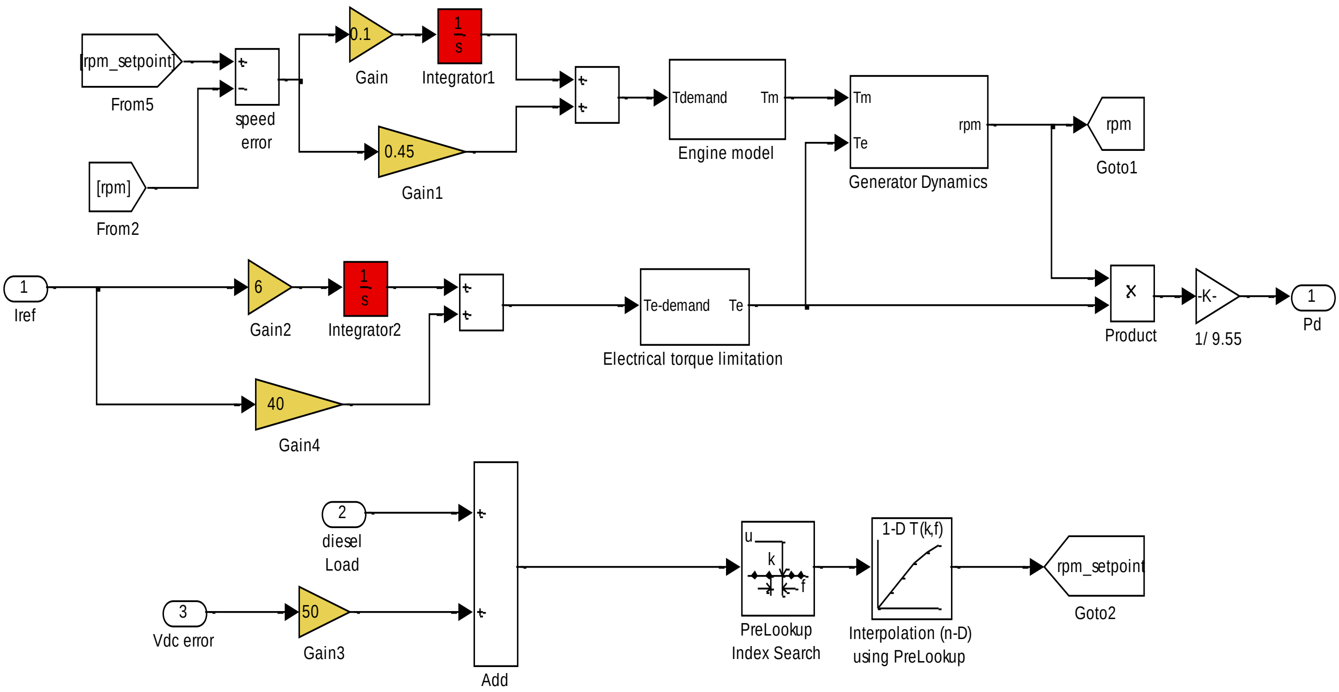


Figure 5.7 - VSDG model

The differential equation below calculates the speed of the VSDG given the power balance into the shaft. The mechanical torque has to balance out with the electrical torque (or power) and frictional losses, or the shaft will be subject to acceleration at a rate proportional to the magnitude of imbalance and the moment of inertia of the system.

$$\omega_r = \int \frac{1}{J} \times \left(T_m - F_{\omega_r} - T_e\right)dt \qquad (5.2)$$

J inertia

T_e Electrical torque

F frictional force per ω_r

T_m mechanical torque

The engine dynamics are based on the response delay and maximum torque. The maximum available torque varies with engine rotational speed, as illustrated in the Figure 5.9.

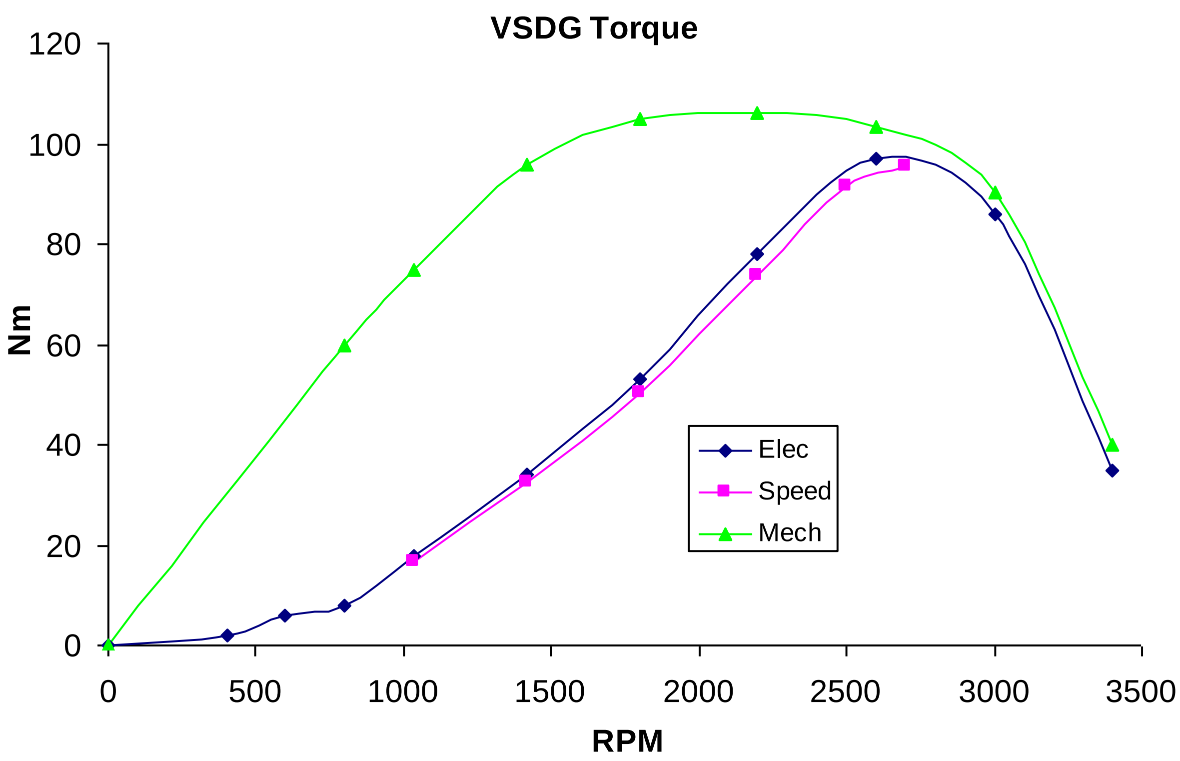


Figure 5.8–Torque speed curve for the electrical generator torque limitation (Elec), speed set point (Speed) and diesel engine (Mech)

A look-up table is used to cross-reference the maximum torque to the speed of the engine, which is the input to T_{limit} in equation 5.3. The response delay *T*, occurs due to fuel movement and actuator delays. The mechanical fuel valve actuator takes time to change its angle to allow more fuel to pass through, which then has to propagate down the fuel pipe into the engine cylinders. The rotational speed of the engine also determines how quickly this fuel is taken into the engine to be burnt.

$$T_m = \frac{1}{Ts+1} \times T_{demand}{}_0^{T_{limit}} \qquad (5.3)$$

T_m Mechanical torque

The delay factor T is proportional to rotational speed and T_{demand} is also speed related.

The electrical torque demand is a simple calculation of the electrical power demand divided by the speed. A dynamic saturation block linked to a look-up table sets the torque limit depending on the rotational speed, illustrated in Figure 5.9 by the "***Elec***" line.

$$T_e = \frac{P_{demand}}{\omega_r} \qquad \textbf{(5.4)}$$

P_{demand} is the electrical power demand

The electrical torque taken from the generator is controlled by electrical current control through the DC/DC converter that links the VSDG to the DC-link. This can be achieved almost instantaneously within the operating range of the electrical generator.

The reference speed set point for the VSDG speed controller is linked to the Power demand and should be made to closely follow the set electrical torque limit as illustrated by the Speed line in the Figure 5.10. The speed set points can be easily and quickly changed to alter the operating characteristic of the VSDG. This could be for the most efficient, least polluting or quietest operation.

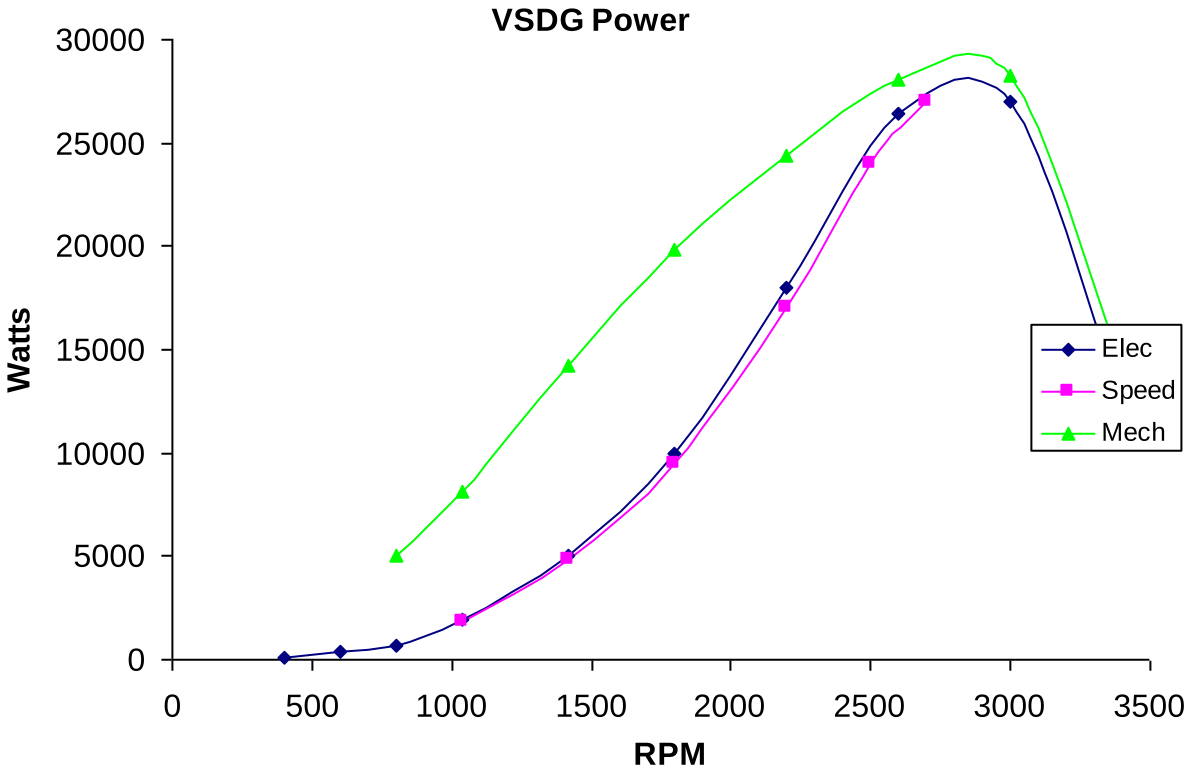


Figure 5.9 - Power speed curve for the electrical generator torque limitation (Elec), speed set point (Speed) and diesel engine (Mech)

5.2.3 Wind Turbine

The wind turbine model (Figure 5.11) comprises of three main parts; Rotor model, equations of motion and electrical torque control.

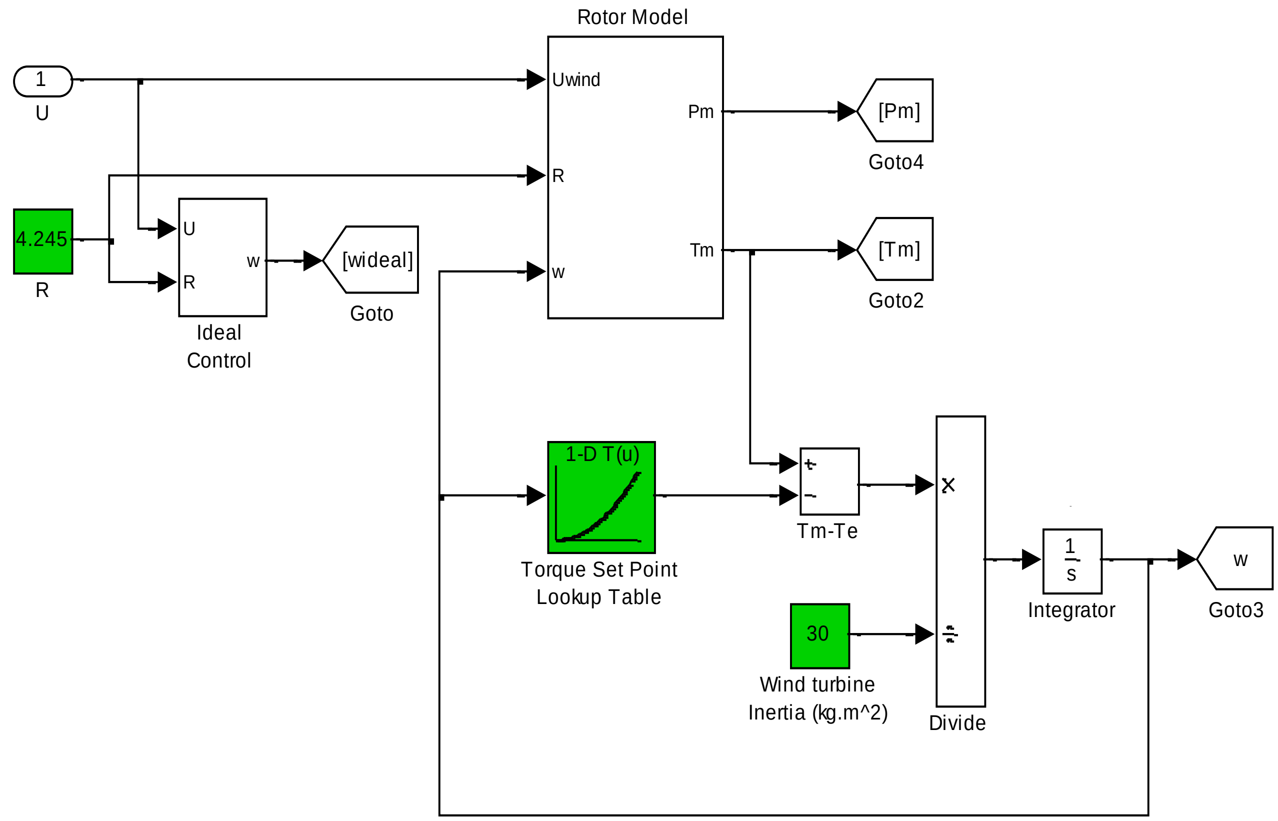


Figure 5.10– Wind turbine model

The rotor model, Figure 5.12, determines the mechanical power input of the wind turbine through the rotor shaft and uses Equations 3.1 and 3.2 from chapter 3.

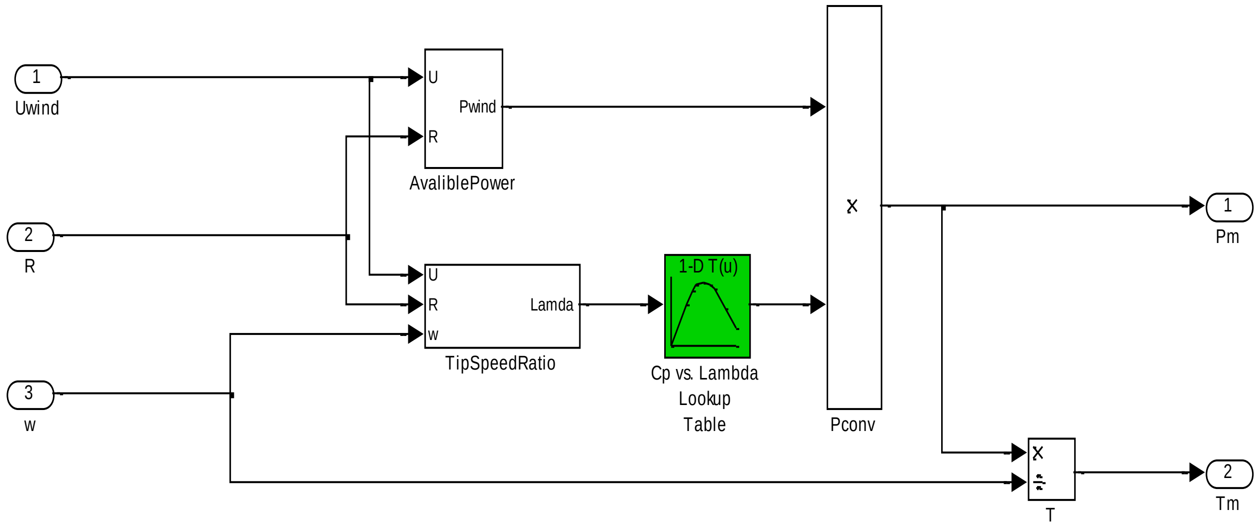


Figure 5.11 – Wind turbine rotor model

The rotor model calculates the power in the wind interactions with the rotor and multiplies this by the aerodynamic efficiency of the rotor blades. The power output versus wind speed for the maximum aerodynamic efficiency operation, also known as the ideal Tip Speed Ratio (TSR or λ) defined in equation 3.2 is shown in Figure 5.13.

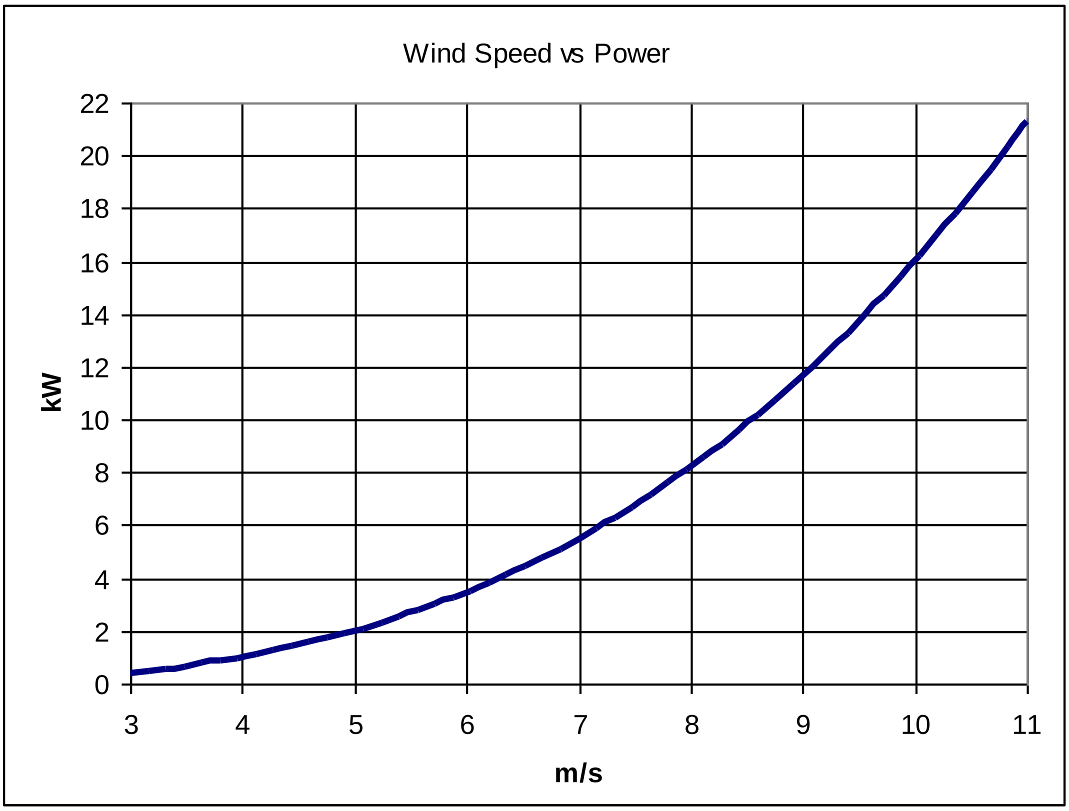


Figure 5.12- Power vs. Wind Speed

The differential equation of motion (equation 5.5) calculates the speed of the wind turbine rotor given the power balance into the shaft. This is similar to that of the VSDG equation of motion, but the frictional forces have been left out due to their negligible effect compared with an internal combustion engine that has many moving parts with seals.

$$\omega_{\mathrm{r}} = \int \frac{1}{J} \times (T_m - T_e) dt \qquad \textbf{(5.5)}$$

The electrical torque control works on the same principle as the DC/DC current controller would in the actual system. The wind speed is unknown, but from the rotor speed the ideal wind speed and therefore power can be inferred assuming constant C_p and knowing λ_{opt}. Dividing the power by the rotor speed gives the desired torque (equation 5.6).

$$T_{wt} = \frac{P_w}{\omega} \qquad \textbf{(5.6)}$$

The wind turbine model is designed to operate from 3 to 11 m/s (400 – 21000W for the 4.245m radius blades) and follow its optimum tip speed ratio (8.876) to achieve the maximum coefficient of performance (0.45). This is achieved through regulating the rotational speed of the blades by altering the electrical generator torque.

5.2.4 PV model

The Simulink PV model is detailed in Figure 5.14, complete with maximum power point tracking (MPPT). The temperature variable in the PV characteristic equations (found in chapter 3.1.3) has been set to 288 K to simplify modelling. In a real system there would be a proportionate rise and fall of cell temperature with solar radiation, the effect of which can be seen in Vigure 5.15. All other PV constants have been based on a Eurosolare PL 800 design (appendix A).

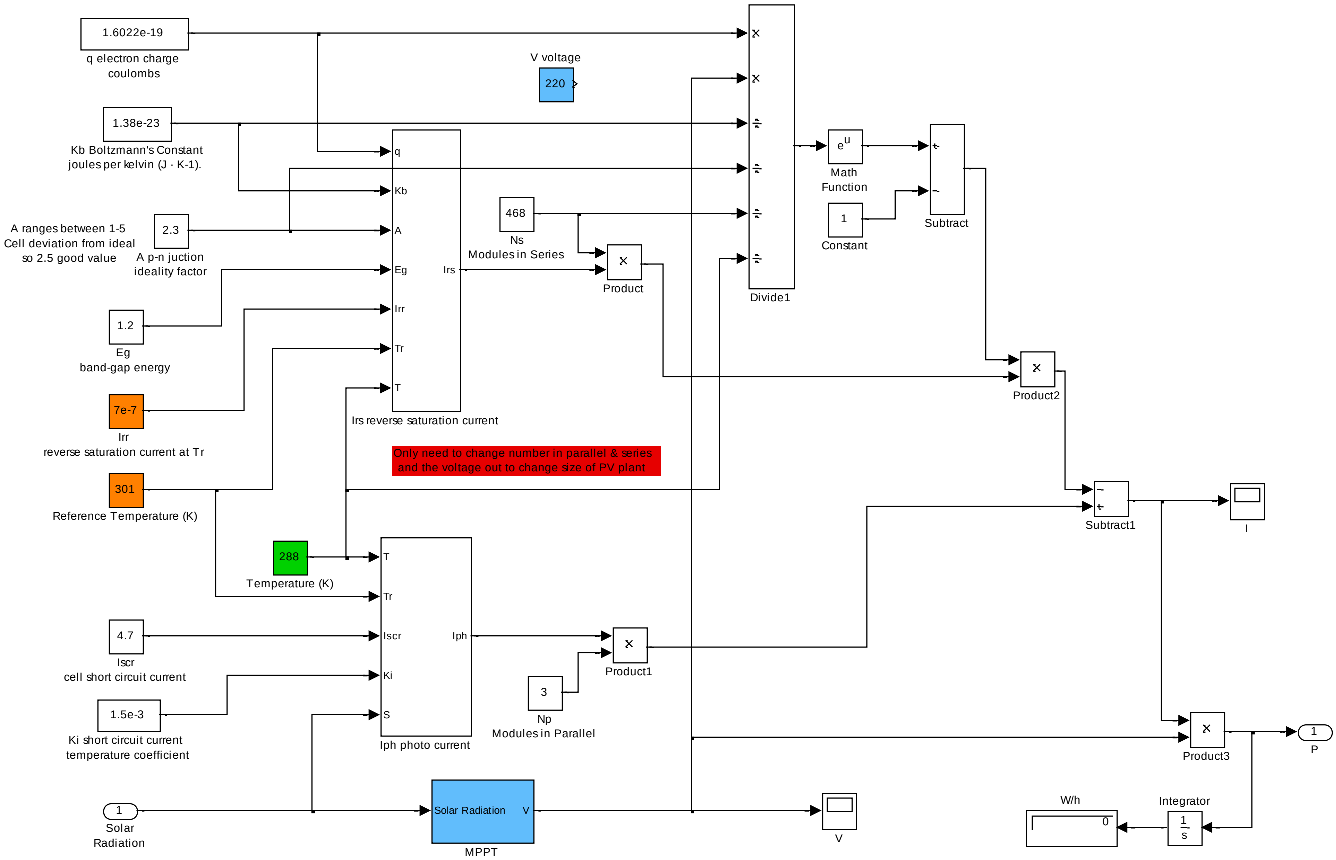


Figure 5.13 – PV model

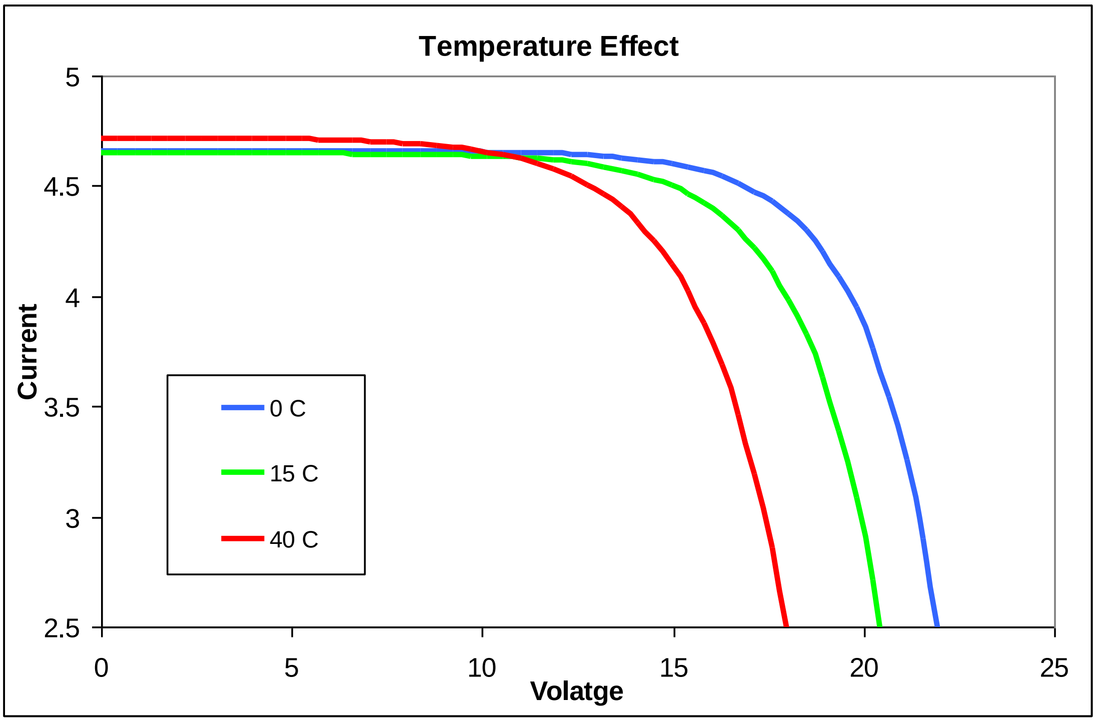


Figure 5.14 – Temperature effect for constant solar radiation

In the PV model, a look-up table is used to set the correct voltage for MPPT given the solar radiation, as shown in Figure 5.16 by the black line. As the temperature T has been set, the maximum power point is set for a given solar radiation. In a real system the change in cell temperature will affect the maximum power set point.

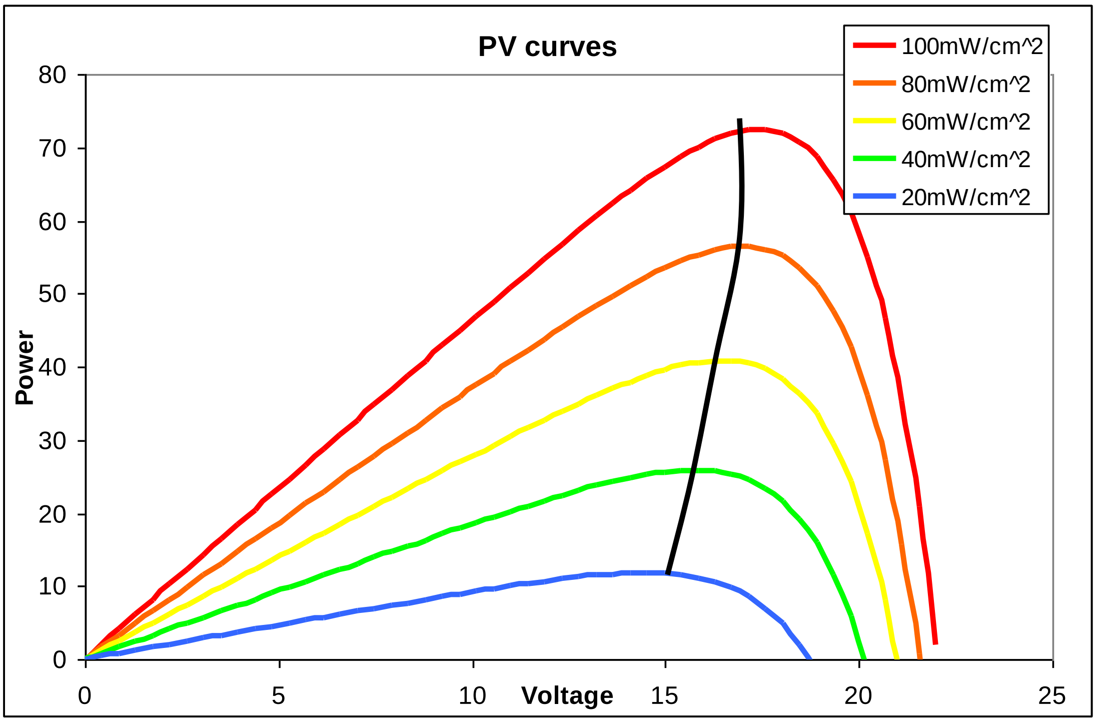


Figure 5.15 – PV module voltage-power curves

5.2.5 Supercapacitors

Supercapacitors can be modelled in the simplest form as a large capacitor using the standard equations of a capacitor.

$$V = V_0 + iR + \frac{1}{C}\int idt \qquad \textbf{(5.7)}$$

$$q = C \times V \qquad \textbf{(5.8)}$$

$$E = \frac{1}{2} \times C \times V^2 \qquad \textbf{(5.9)}$$

Some supercapacitors, depending on material composition, have been found to have a slight voltage varying capacitance, which can be modelled by equation 5.10.

$$C_{tot} = C_i + C_v \times V \tag{5.10}$$

C_i is the initial capacitance
C_v is the voltage varying capacitance

They can also be modelled in more detail by increasing the number of resistor capacitor branches for different time domains.

The total capacitance for multiple capacitors in series is calculated using the equation 5.11 and for capacitors in parallel using equation 5.12.

$$C_{series} = \frac{C_1 \times C_2}{C_1 + C_2} = \frac{C^n}{n \times C} \tag{5.11}$$

n is the number of identical capacitors

$$C_{parallel} = C_1 + C_2 + C_3 = n \times C \tag{5.12}$$

Supercapacitors are double layer capacitors that have a very small effective distance between the plates and a large surface area thus increasing their capacitance in accordance with equation 5.13 below.

$$C = \varepsilon \times \frac{A}{d} \tag{5.13}$$

$\boldsymbol{\varepsilon}$ is permittivity of the dielectric
$\boldsymbol{d}$ is the distance between the plates

The supercapacitor system control scheme limits the electrical current to a set maximum (saturation blocks in Figure 5.17) and controls charging and discharging. It is allowed to operate between set voltage limits (typically 50-100%).

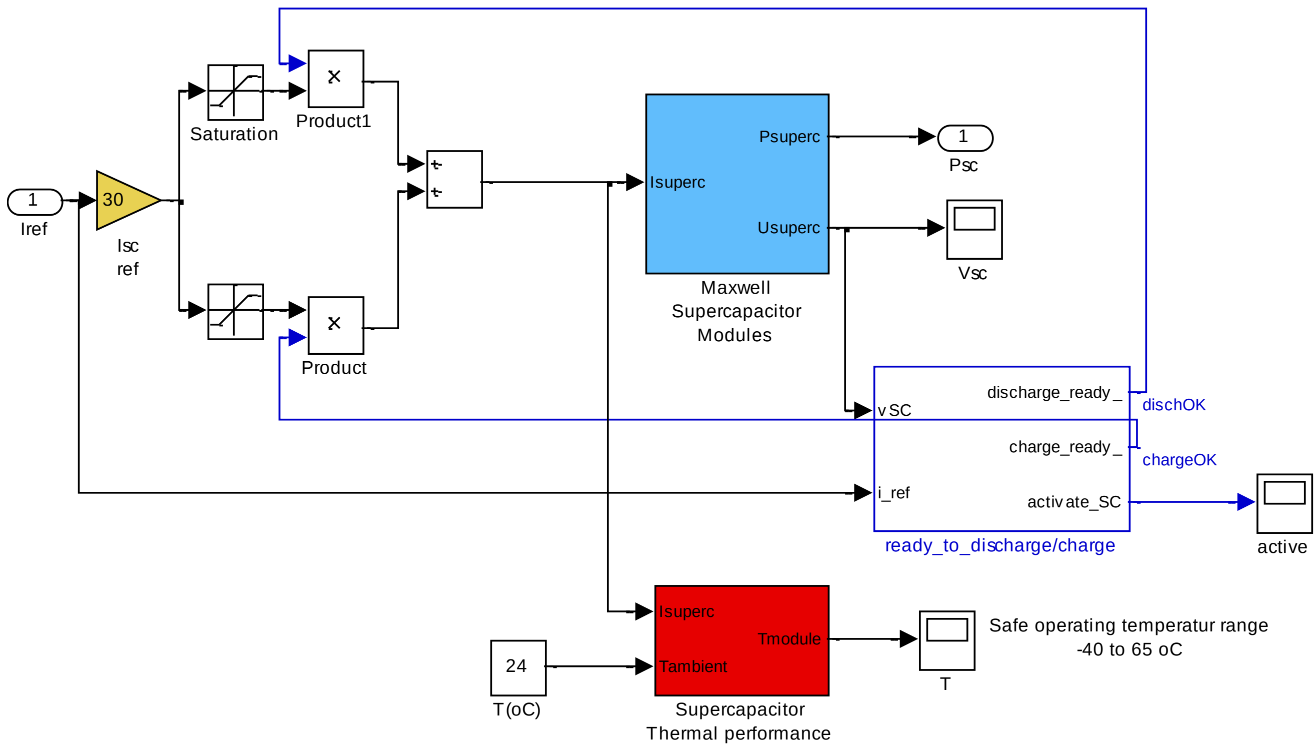


Figure 5.16 – Supercapacitor model

The controller checks to see if the Supercapacitor system voltage is suitable for charge or discharge and then cross checks this with the required operation to allow activation of the system, Figure 5.18.

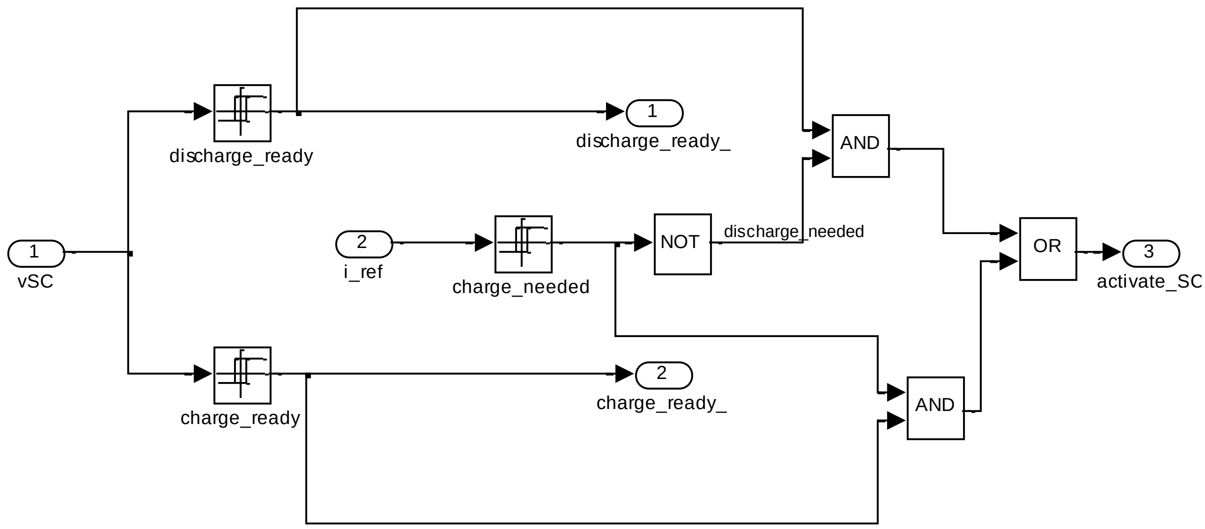


Figure 5.17 – inside ready_to_discharge/charge subsystem

5.2.6 DC-link model

The DC link is modelled using equation 5.14 and is simply the power balance on the capacitor voltage.

$$V_{dc} = \sqrt{\left(2 \times \frac{1}{C} \times \int_0^t \sum P dt + V_o^{\,2}\right) dt} \qquad \textbf{(5.14)}$$

The initial voltage V_0 is 500 volts and the capacitance is 8 milli-farads.

5.2.7 VSDG stability - test and results

To demonstrate the stability differences between the VSDG and constant speed diesel, the VSDG was subjected to a 3kW step load increase from an original load of 6kW without electrical generator current limitation. Figure 5.19 illustrates the effective stalling of the engine as the rotational speed drops to zero. Figure 5.20 illustrates the VSDG response to a 2kW step load with the same initial conditions as before. As can be seen the engine is able to accelerate up to the new set point and thus shows stable operation.

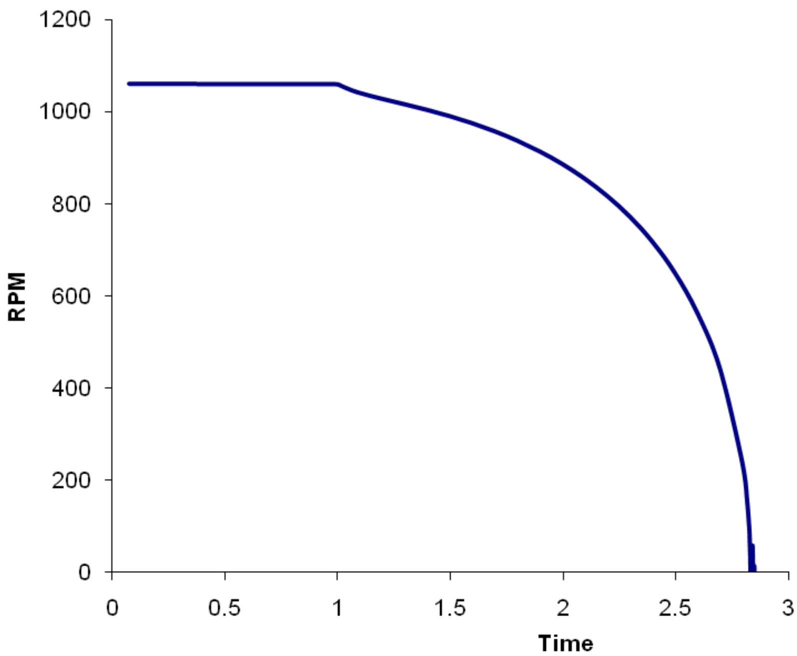


Figure 5.18- 3kW step load increase

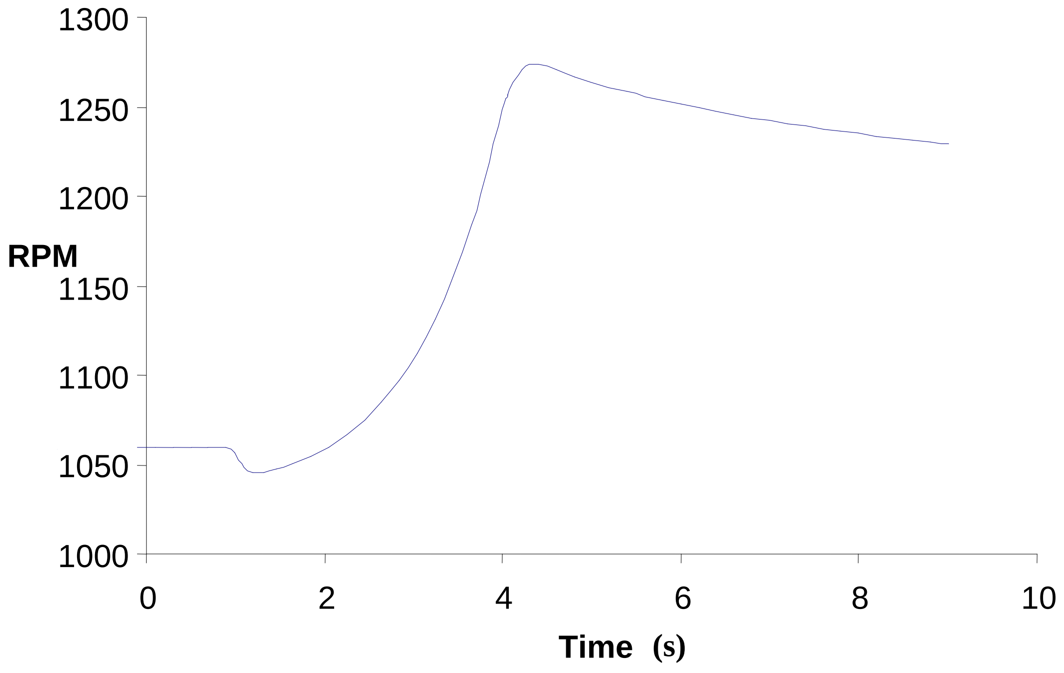


Figure 5.19 - 2kW step load increase

The constant speed diesel generator is able to undertake much bigger step load changes and still operate satisfactorily. Figure 5.21 shows the frequency dipping to only 49.2Hz from the 50Hz reference value under an 8kW load step from a 6kW initial load.

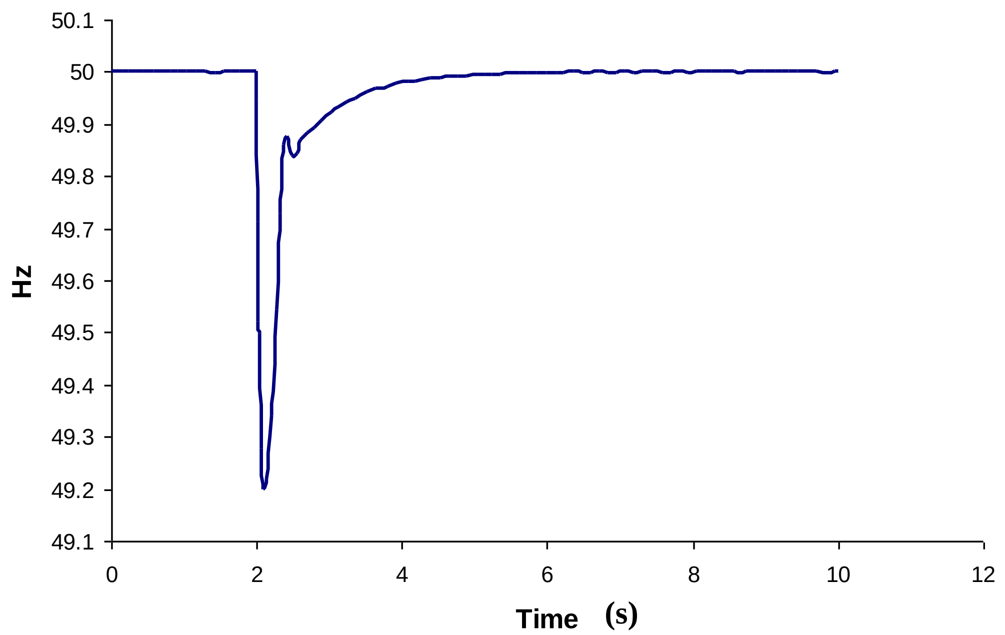
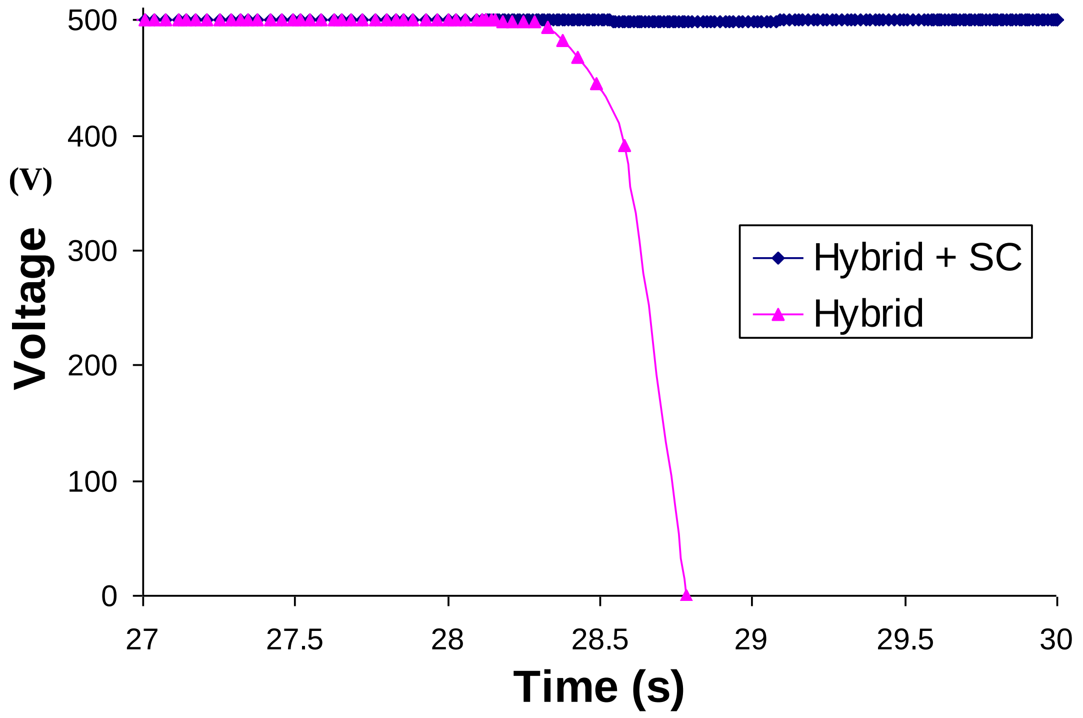


Figure 5.20 - Constant speed frequency response to a 6-14kW step load increase

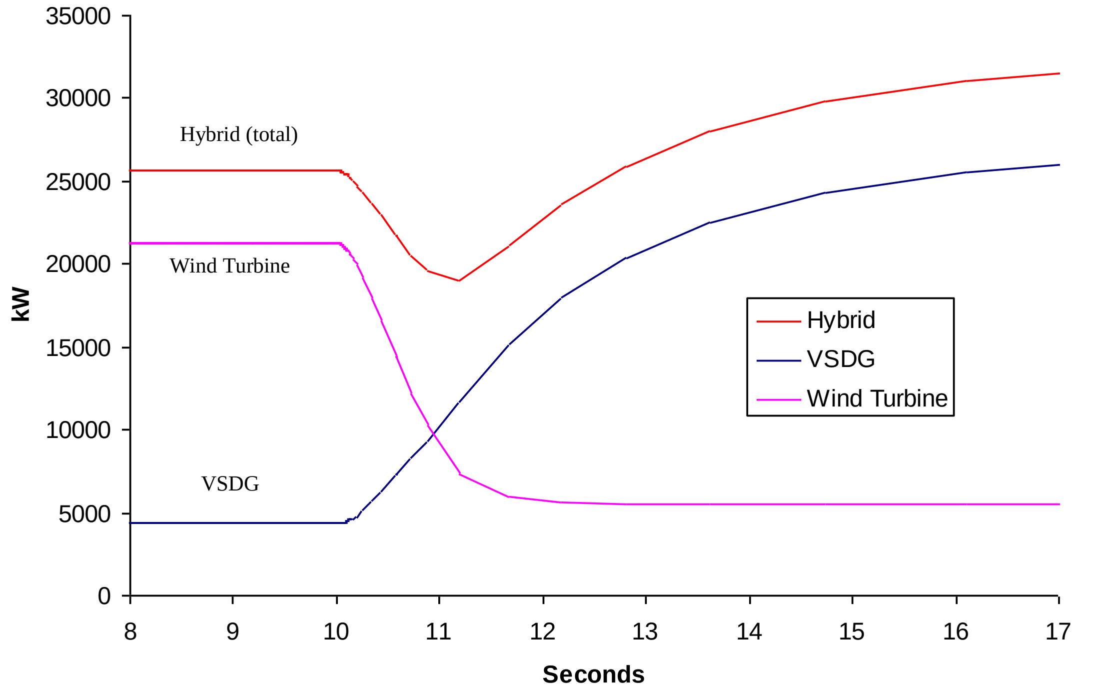
5.2.8 Hybrid system DC-link voltage drop - test and results

One way to achieve safer operation of the VSDG is to have a torque limitation scheme for the electrical generator. This follows the diesel engine maximum torque to avoid engine stalls. Generator torque is a function of generator current, so by limiting the current through the DC/DC converter the torque can be regulated. This then causes a reduction in power supplied and therefore a voltage drop across the DC-link capacitor of the AC/DC/AC converter.

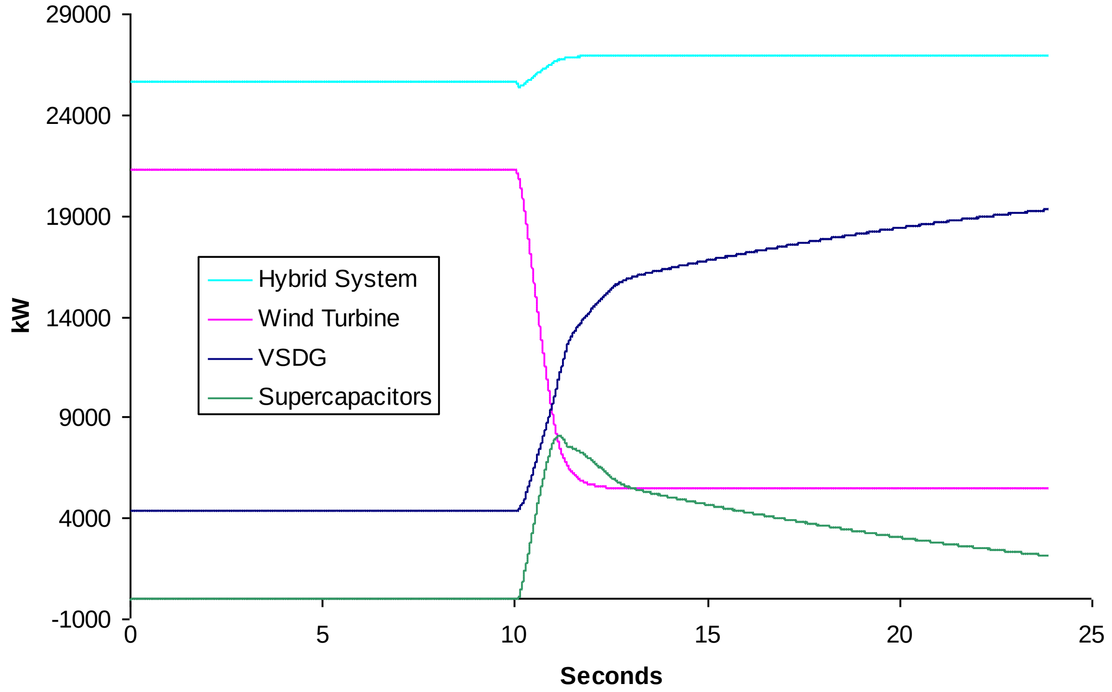
To test this proposed method, the hybrid system was subjected to a wind speed reduction from 11 to 7 m/s. The wind turbine power loss causes the DC-link voltage to crash (500-0V) as illustrated in Figure 5.22(a). The voltage drop would be directly imposed onto the inverter output, causing a blackout over the grid, which could take a substantial amount of time to re-establish.



(a) DC link response



(b) Wind-Diesel hybrid Power flow



(c) Wind-Diesel-Supercapacitor hybrid Power flow

Figure 5.21– Hybrid System Wind Drop

From Figure 5.22 (b) the shortfall in supplied power between 10 and 11 seconds corresponded to the loss of DC-link voltage. The VSDG initial pick up is good and engine stall is avoided, but it is unable to match its extra load demand caused by the wind turbine power drop. The VSDG has an added DC-link voltage controller that increases the power output to help bring the voltage back up to the set value.

The addition of the super capacitor system (300V 2.9F) results in a much more stable DC-link with a voltage drop to only 499.5V under the same wind change as before, Figure 5.22 (a). The drop in wind power causes the supercapacitor system voltage to drain from 289 to 156V, which is equivalent to 0.02kWh or 70% of the total energy stored, while helping maintain DC-link voltage. It can clearly be seen in Figure 5.22 (c) that the super capacitor system helps the VSDG maintain system stability under renewable power transients.

5.3 Power Balance

Initially, real world load data for a suitable sized community over a time period of days was sought, but no detailed data was available except from that for Foula. In order to provide the hybrid models with accurate load data, a detailed bottom-up load model has been created.

On small island grids, individual items have an increased effect on the grid stability, and thus the model has been detailed to this level. In the model, a defined time window has been given for each action to take place (like waking up, putting the washing on etc). A random number, which is created for each day or event, is then added onto the start of the time window to determine when that action will start.

Example: Wake up has to occur between 7:30am and 8am. Hence, the time window starts at 7:30am and ends at 8am. The random number can be limited to a specified range, in this case between 0 and 30. The random number, which for this example will be 7, is then added on to the start time so the person wakes up at 7:37am.

Household Individuals have been given attributes, so they cannot perform impossible or unlikely task, such as vacuuming while using the computer and listening to the radio.

The process can be quite labour intensive, even after all the individual items have been created as each household can have a different makeup and requires different time windows and random number series for every task. There are a lot of different interactions occurring in an individual household that define which devices are being used and when. In small communities of 20 to 100 households, for which the hybrid system is intended, this is an acceptable method for creating a detailed load model, but for larger communities it would start to become cumbersome.

5.3.1 Setup/test

Each electrical device has a real/active power, standby power and Power factor associated with it. From this, the reactive power and the real instantaneous power that the hybrid system has to supply can be calculated.

$$S = \sqrt{P^2 + Q^2} \qquad \textbf{(5.15)}$$

$$p.f. = \cos\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} \qquad \textbf{(5.16)}$$

$$S = \frac{P}{p.f.} \qquad \textbf{(5.17)}$$

Items have been sorted into different categories

- Electronics and entertainment,
- Lighting
- Motors
- Electrical Heating

Electronics and entertainment loads consist of small rectifier and SMPS loads, such as TVs, PCs, Radios and Satellite receivers. Small loads are classed as those below 75W, and therefore do not require power factor correction, whereas devices above

75W are required by law to maintain a given power factor under regulation standard EN61000-3-2.

Small single phase motors can be found in fridges, washing machines and other small pumps and fans throughout the property (heating pumps, ventilation fans, vacuum cleaner etc).

Electrical heating usage mainly consists of electrical fan and radiant heaters, food and water heating, microwaves and irons.

Cat	Type	p.f.
Electronic	Rectifier (<75w)	0.63
	SMPS (>75w)	0.98
Lighting	Incandescent	0.99
	CFL	0.95
	Fluorescent	0.9
Motors	1-Phase Induction	0.83
Heating	Space/ Water	0.99
	Microwave/Iron	0.83

Table 14– Device Power Factor (p.f.)[79]

Table 5.3 lists the power factors for the different devices used in the load model.

The scheduling of these devices is controlled by an S-R Flip-Flop (Table 5.4: truth table) and relay blocks in Simulink as laid out in Figure 5.23.

S	R	Q	
1	0	1	
0	0	1	(after S == 1, R == 0)
0	1	0	
0	0	0	(after S == 0, R == 1)
1	1	0	

Table 15 – S-R Flip-Flop operation table

The relays reference the actual time of day (or week for non daily activities) to the random start time and also the random start time plus the random usage time (or run time). This gives the switch on and switch off time for the device.

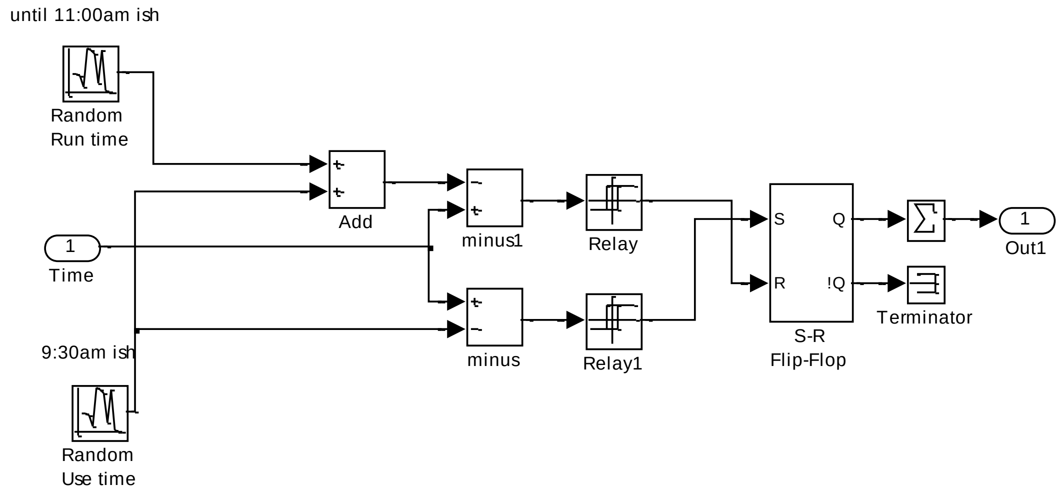


Figure 5.22 – Device scheduling model

Relay1 is switched on when the actual time is greater than the random use time (and the output from the real time minus random start time block is positive) giving a logic high/true signal (1) into the S-R flip-flop input S. At this time, the S-R flip-flop input R is receiving a logic low/false (0) signal because the output from the real time minus random start time plus random run time block is still negative giving a logic low/false signal (0) from the relay. Therefore, the output of the S-R flip-flop Q is logic high/true turning on the device being controlled. When the real time is greater than the random use time plus random run time the S-R flip-flop input R changes to logic high/true (1) and the output of the S-R flip-flop Q switches to logic low/false, causing the devices to be turned off or switched on to standby. The mean and variance of the random number sequence can be altered to give the desired operation time. Different seeds are needed, so that blocks do not have identical random numbers, if they have the same mean and variance. This method only allows one switching per sample time (period), but this sample time can easily be altered in the random number block parameters.

Figure 5.24 shows an overview of the whole model and the following Figures look under the mask of the subsystems within the lighting load category.

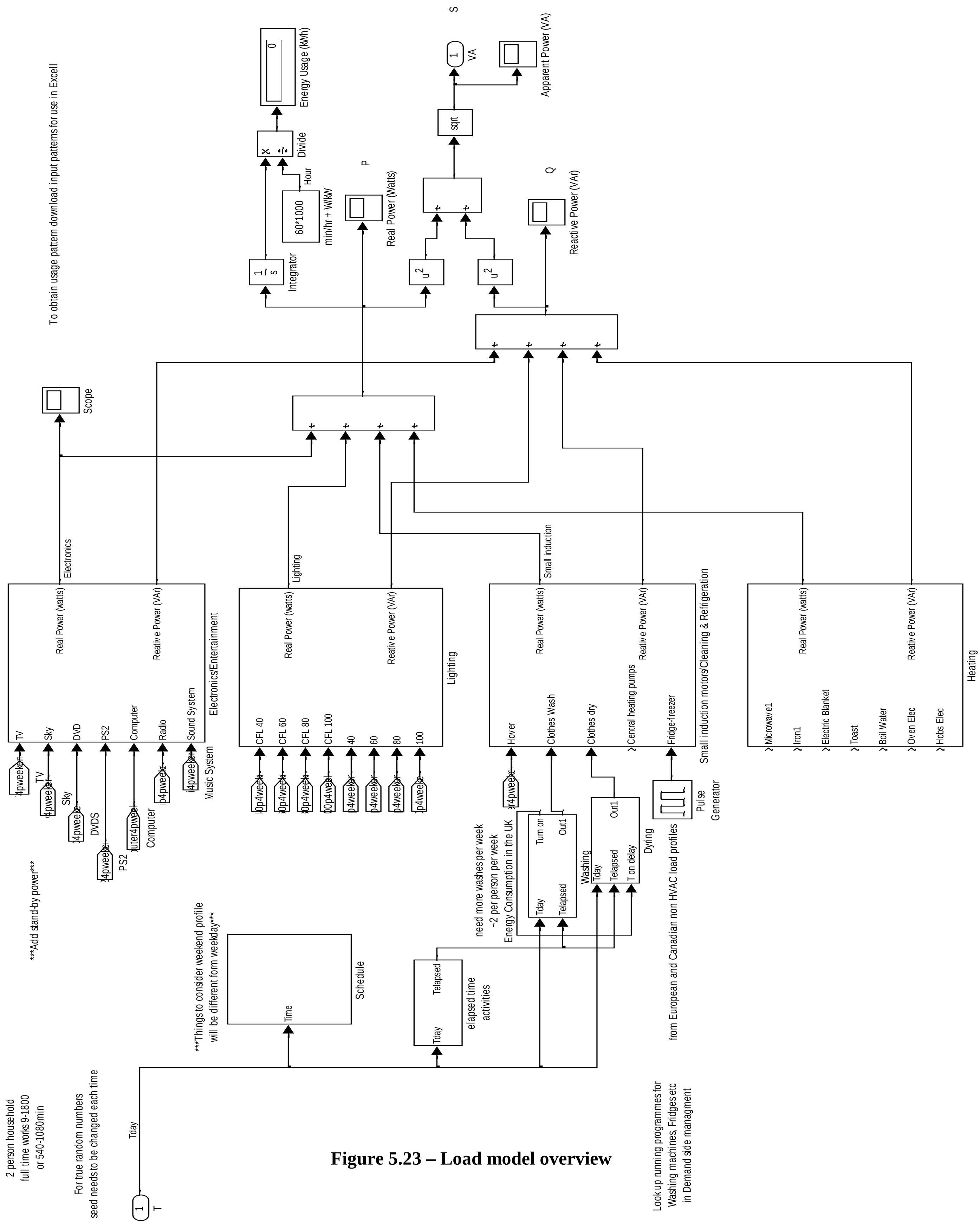


Figure 5.23 – Load model overview

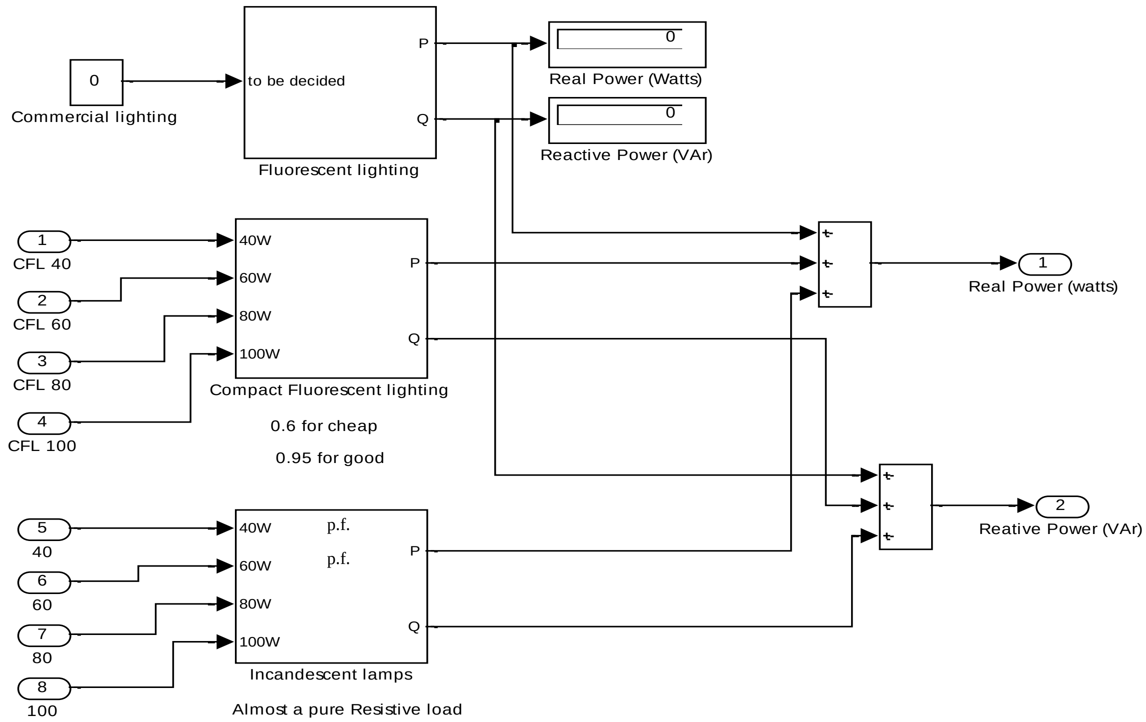


Figure 5.24 – Inside lighting subsystem

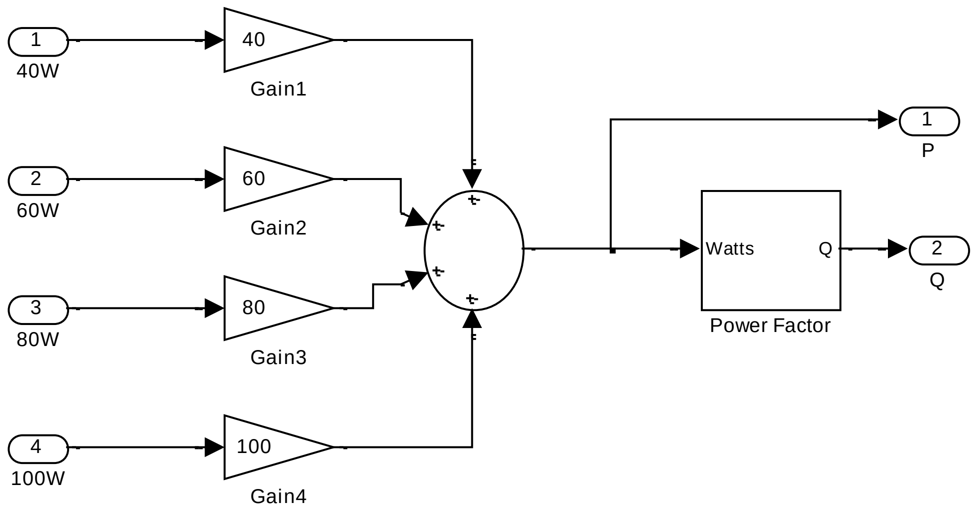


Figure 5.25 - Inside incandescent lamps subsystem

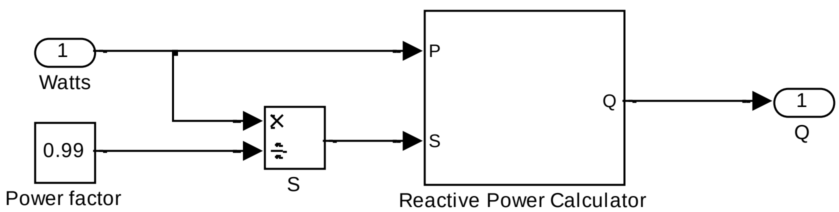


Figure 5.26 - Inside power factor subsystem

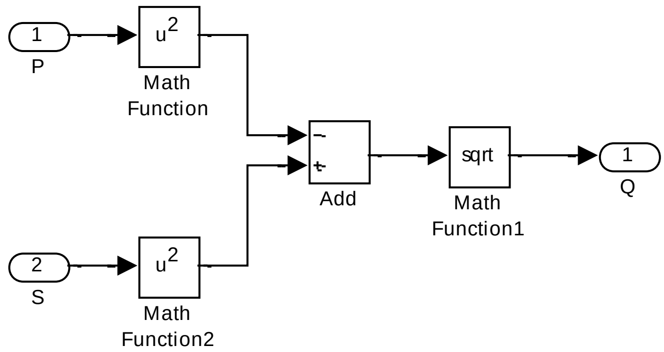


Figure 5.27 – Reactive power calculator

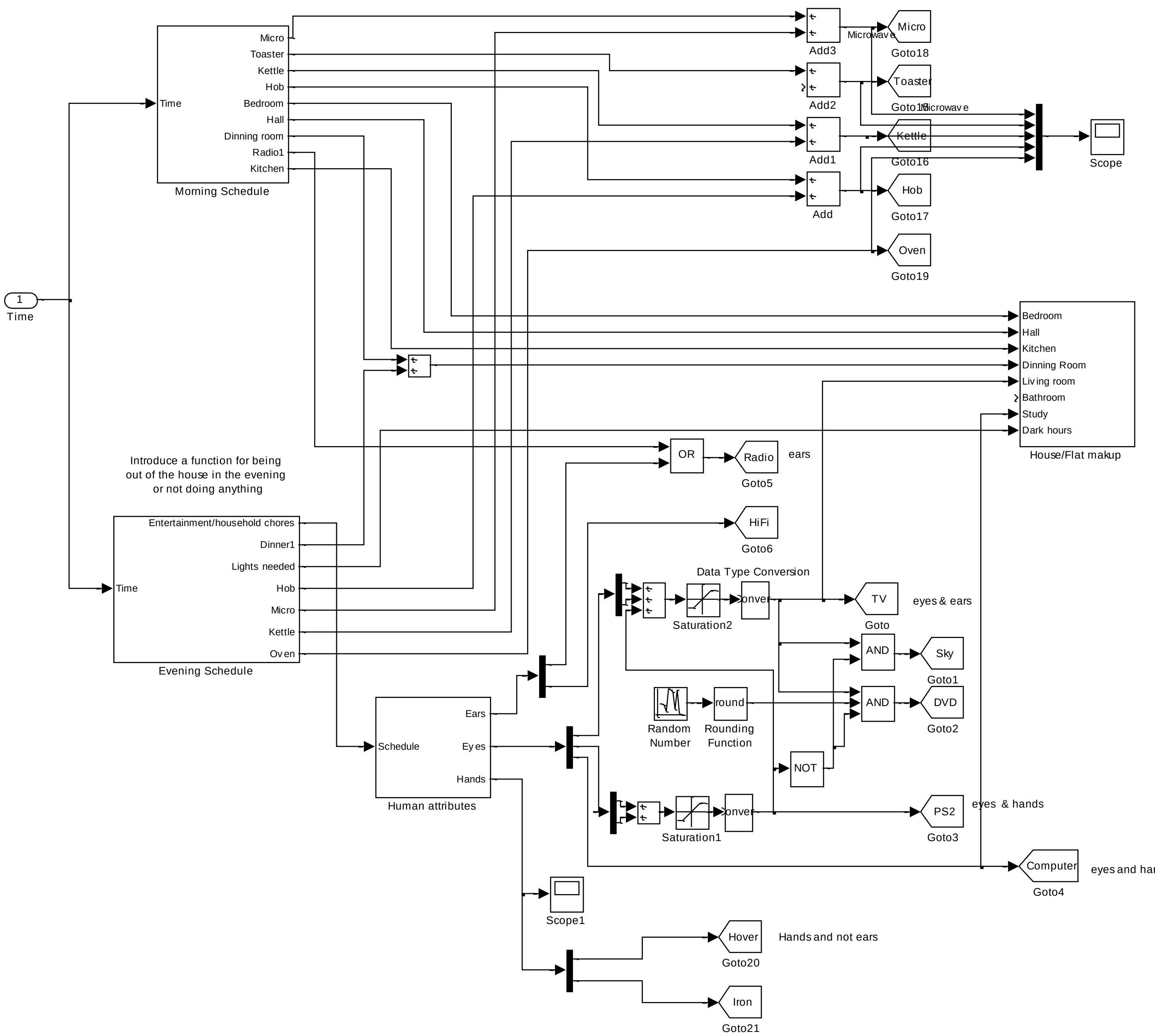


Figure 5.28 – Scheduling overview

In each household or building with human occupancy (School, office etc), the first decision to be made is the number of people in the building. Occupancy patterns, which largely rely on the employment type of the people within the building (Part-time, full time etc), are chosen next, see Table 5.5.

Type	*Unoccupied period*
Part time	9-13:00, 17-22:00 etc
Full-time	9-18:00
Not working/unemployed	various
Night shift	20:00-9:00

Table 16 - Household occupancy pattern examples

The design of the building and composition of devices in each room (lighting and other devices) then has to be determined. Links can be made between rooms and the devices for example so that when the TV is on in the living room the lights are on as well (if it is dark outside). An overall control for the hours that lights are needed can be easily implemented using a seasonal variation for the hours of darkness in the region being studied (although dark hours would also depend on cloud cover, this could be implemented by adding a random number element that would be specified to represent the historical weather data (cloud cover/hours of darkness) of the area). Links can also be made between devices, so that DVD players and games consoles require the TV to be on.

For many appliances, device usage is directly linked to available human attributes, which consists of ears, eyes and hands. Many appliance tasks require more than one attribute such as using the computer, which requires hands, eyes and sometimes ears. Other tasks effectively obstruct the use of some attributes. Vacuuming is one example of such a task, as it uses the hands and eyes and obstructs the use of the ears.

Many devices can be used by multiple people at the same time and therefore use more attributes (for example people watching TV, playing games or listening to music together).

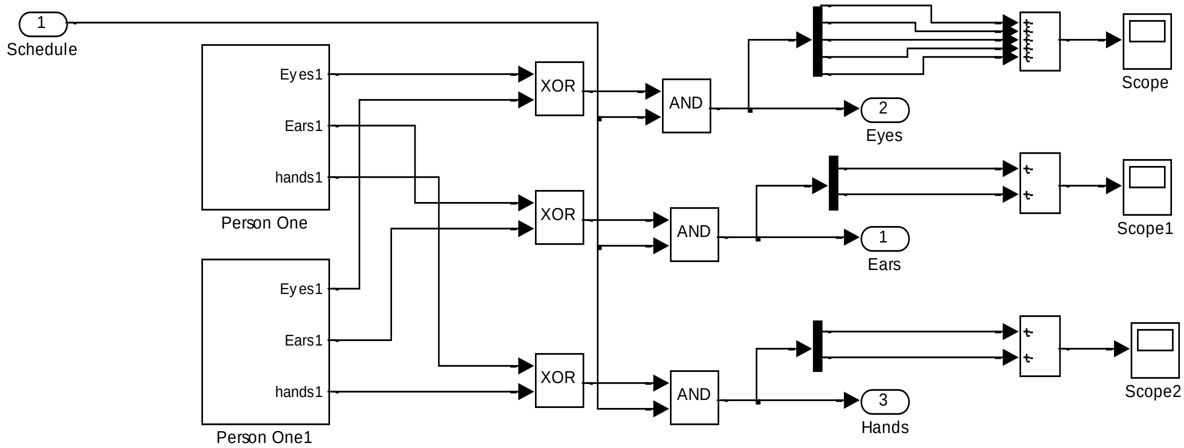


Figure 5.29 – Human attributes overview

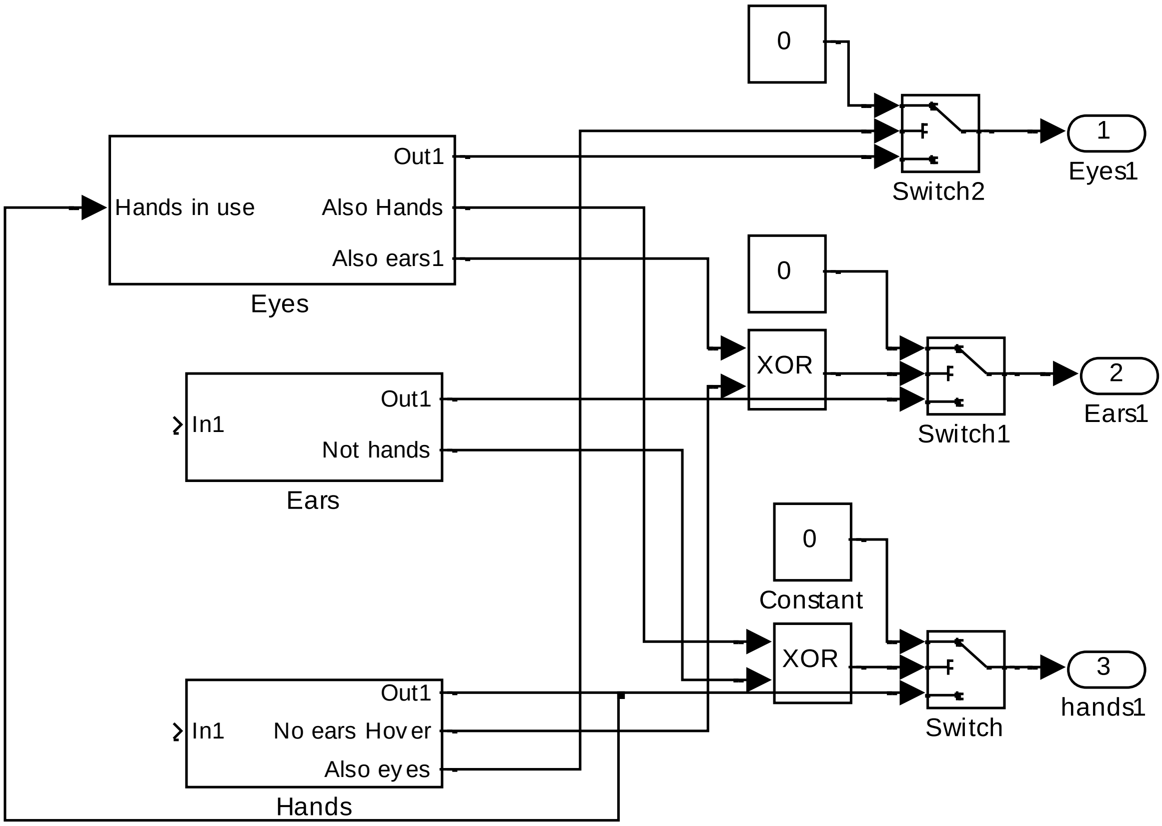


Figure 5.30 – Person one subsystem

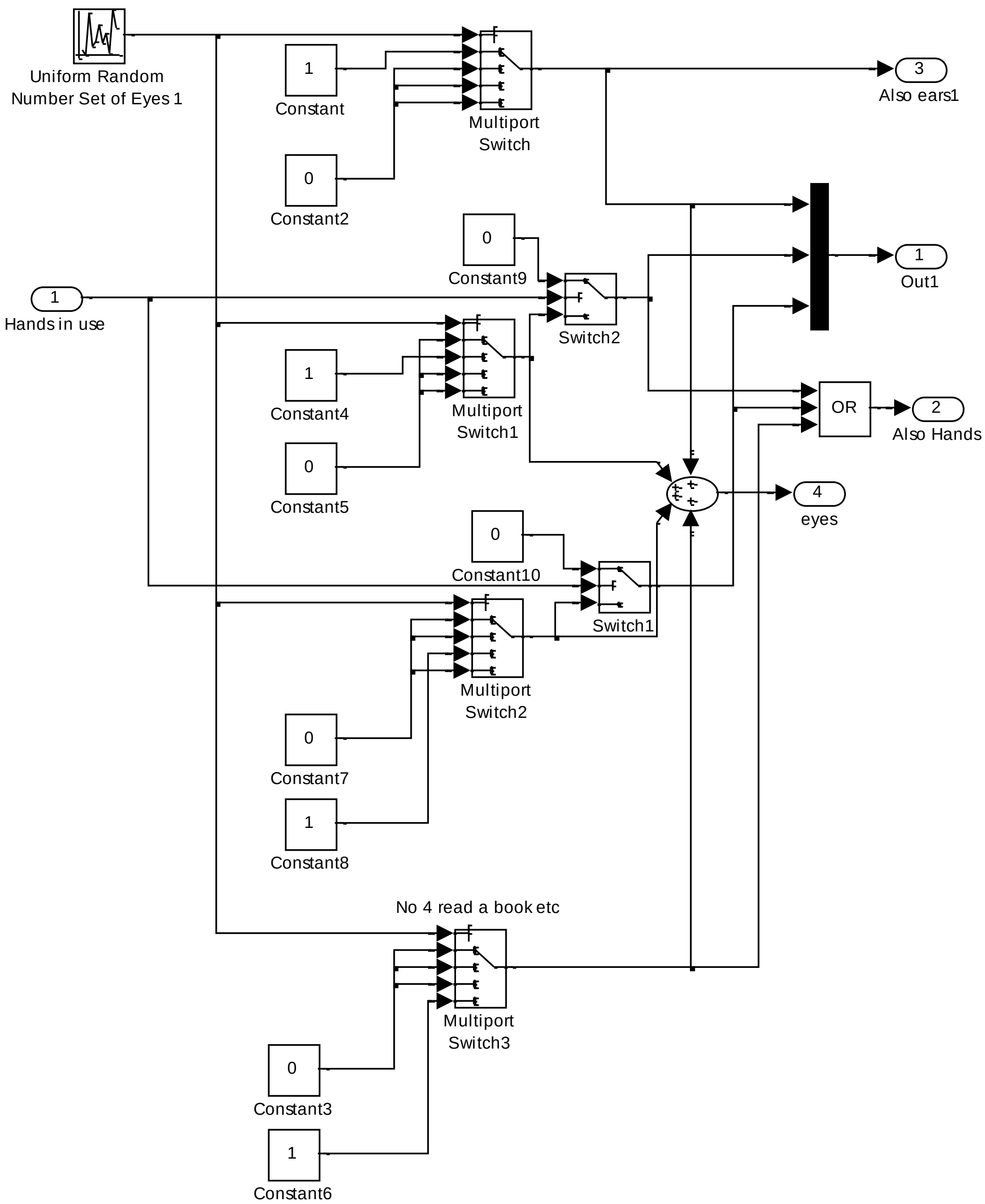


Figure 5.31 – Eyes subsystem

The schedule input in Figure 5.30 controls when household members wake up and go to sleep, which is taken into account for device usage and task execution. Figure 5.31 shows the logic gates and switches used to control the possible tasks and attribute combinations. Inside each attribute (eyes, ears & hands) subsystem, a uniform random number generator (which generates a random number between the set maximum and minimum) is used to select a task. The random number selects a port in a multiport switch, which is linked to a task as shown in Figure 5.32. A state is also given to tasks not requiring electrical devices (multiport switch3) such as reading a book or being outside gardening.

Other tasks require no continued human attributes once started. These are also known as time elapsed/non effort driven tasks in project management. Examples of these are washing machines, dishwashers and to a certain extent some cooking appliances (ovens, microwaves etc). Some of these devices can have time delays set, so that they come on when the house is empty.

Devices that run through a programme, for example washing machines and dishwashers, require a more complex model than a simple on/off switch.

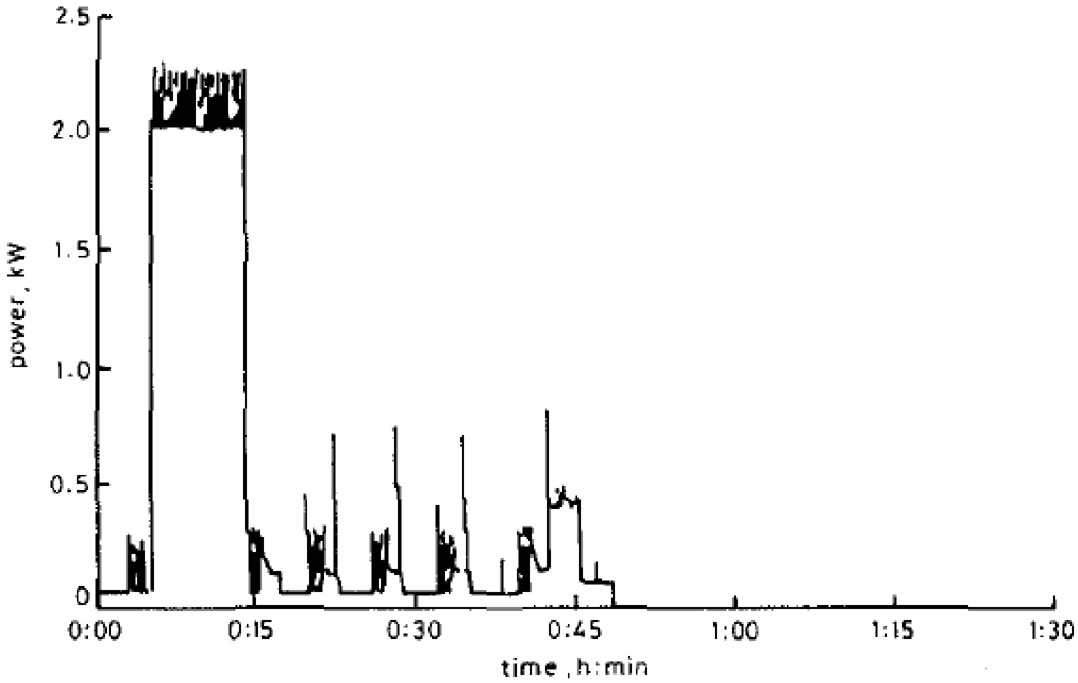


Figure 5.32 – Washing machine load demand on 40^{o}C cycle [69]

Figure 5.33 demonstrates a load pattern of a washing machine on a 40^{o}C cycle. The first large load period is for the water heating (therefore this period will increase or decrease with wash temperature setting). The subsequent load spikes are the cleaning cycles with a large spin cycle at the end. Wash patterns vary between machines and most machines have a large range of wash options. Many of these more complex loads will also have power factors that vary. In the initial stage of water heating, the p.f. will be close to that for pure resistive heating (p.f. 1). During the wash and spin cycles, the load is mainly that of a single phase induction motor (p.f. 0.83).

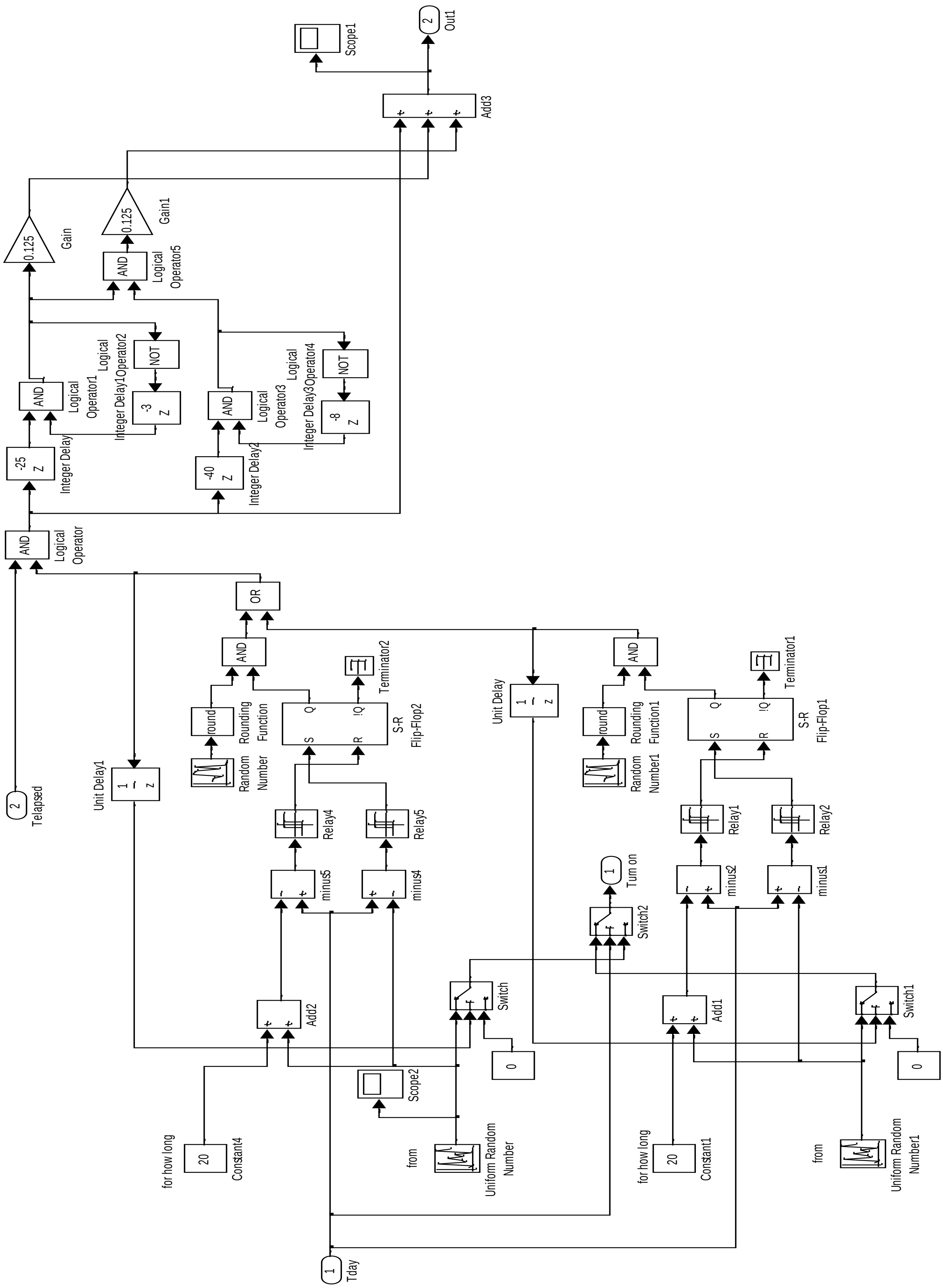


Figure 5.33 – Washing machine load pattern model

Information is available on a number of washing cycles and other more complex loads. The energy use of the load programmes has been compared to the average energy usages found in literature to help validate the model. Figure 5.34 shows the load model for the washing machine.

The same building can have a significantly different usage pattern during the week compared with the weekend. This necessitates two different models for most building to cover the whole week. The models will have the same composition, but the occupation and task patterns will alter.

All these models combine to allow complete characterisation of the individual household or building. These collectively amalgamate to form a detailed complete community aggregate load.

A power system was created to supply the community load. The power balance model incorporates some of the power system dynamic model of the hybrid system from the previous section, which has been modified to run on a one minute time period. The model is simulated over a 14 day run time. The hybrid system is similar to that already used in the power system dynamic model comprising of a 28kW diesel generator, 20kW wind turbine, 3kW PV system and supercapacitor system as shown in Figure 5.35.

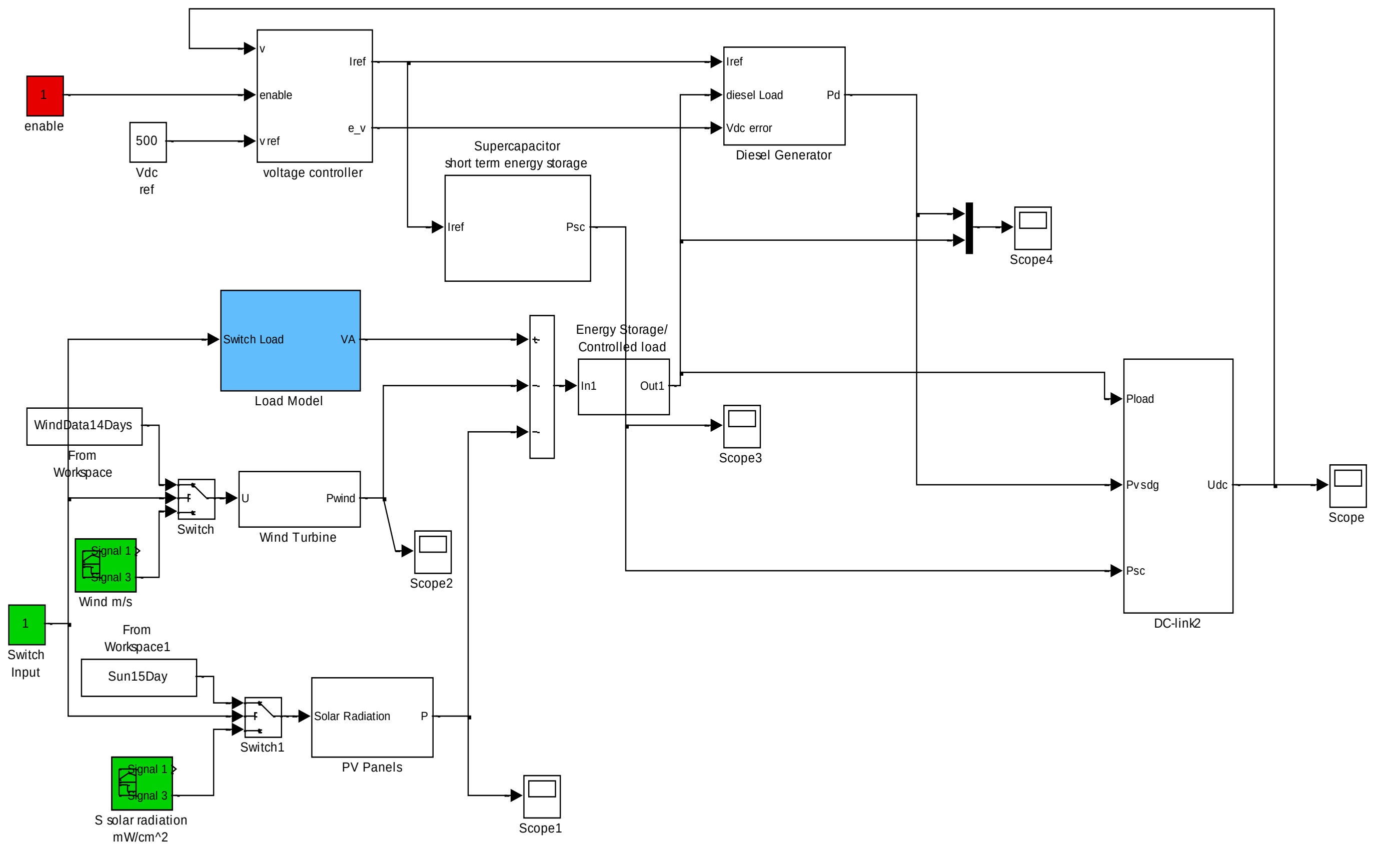


Figure 5.34 – Power Balance hybrid model

5.3.2 Resource

Wind speed data has been obtained from the national climatic data centre, USA National Oceanic and Atmospheric Administration. The mean wind speed over the 14 days of real data used in the simulation, shown in Figure 5.36, is 6.4m/s. This is a lower mean wind speed than the good wind sites where hybrid wind diesel system are likely to be placed and therefore will have a smaller wind penetration. The mean wind speed at a 10m hub height for Foula is 10.3m/s and for the main Shetland Islands is 7.3m/s [70].

For the 20kW wind turbine used in the simulation, the wind profile in Figure 5.36 produces 1 -13kW of power.

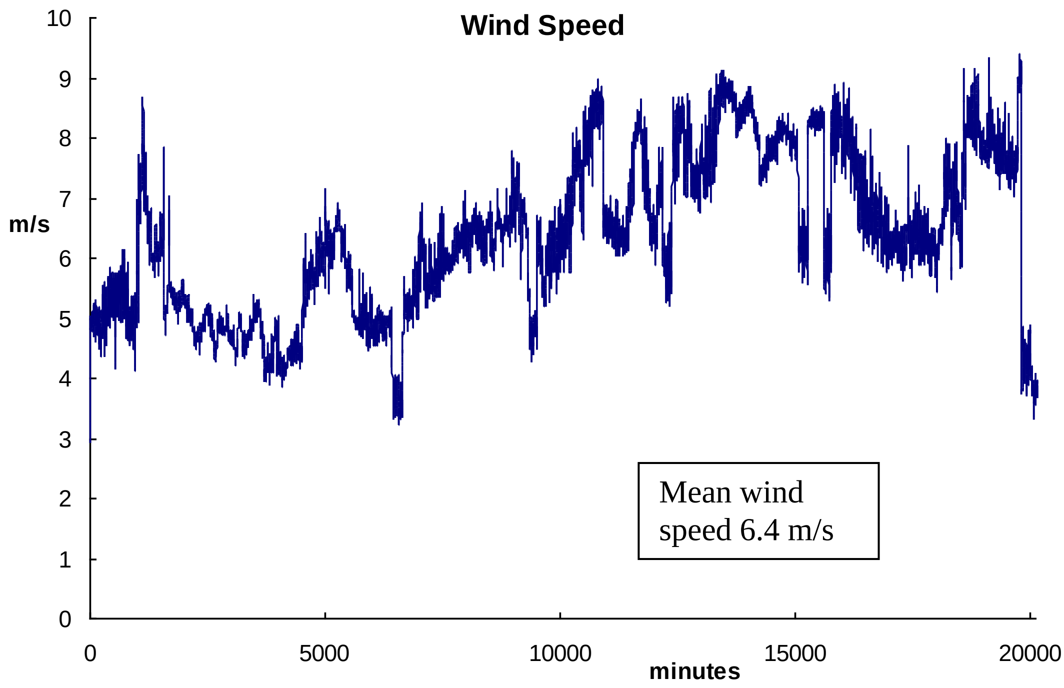


Figure 5.35– 14 day wind speed data [71]

Solar radiation data for the 14 days has been obtained from the automatic weather station at Macquarie University, Australia [72]. The average daily radiation in northern Scotland changes during the year from as little as 0.13 kWh/m^2/d during the winter to 5.15 kWh/m^2/d in the summer. The average for Scotland is 2.46 kWh/m^2/d or 900kWh/m^2/year [73].

The average daily solar radiation energy for each month of the year is shown for two Scottish Islands, Foula and Fair Isle, in tables 5.6 and 5.7 below.

Lat 60 Lon -2	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-year Average	0.28	0.86	1.92	3.50	4.84	5.01	4.59	3.79	2.43	1.20	0.40	0.16

Table 17 – Monthly average solar energy for Foula in kWh/m^2/d [74]

Foula has an average daily solar radiation of 2.415 kWh/m^2/d and Fair Isle has an average daily solar radiation of 2.595 kWh/m^2/d.

Lat 59 Lon -1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-year Average	0.34	0.99	2.11	3.71	5.21	5.34	4.87	4.01	2.61	1.29	0.46	0.20

Table 18 - Monthly average solar energy for Fair Isle in kWh/m^2/d [74]

The average solar radiation for the simulation data over the 14 days is 3 kWh/m^2/d and therefore would be representative of summer months in the UK. The solar radiation profile for one of the 14 days is illustrated in Figure 5.37 below.
The PV panels are modelled on a Eurosolare design that has a peak power of 3kW.

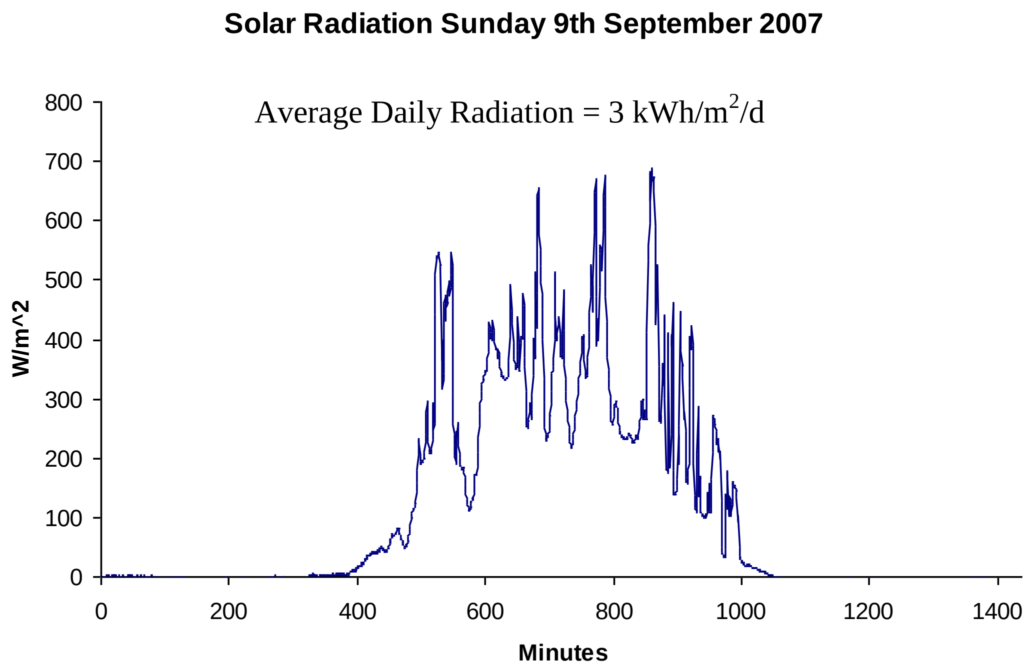


Figure 5.36 – Solar radiation profile

5.3.3 Results

Average load over the 14 days is 7,628 W with a peak of 25kW and a base load of about 5kW, as shown in Figure 5.38. It should be noted that there are no large industrial loads such as induction motors or electric welders in the model.

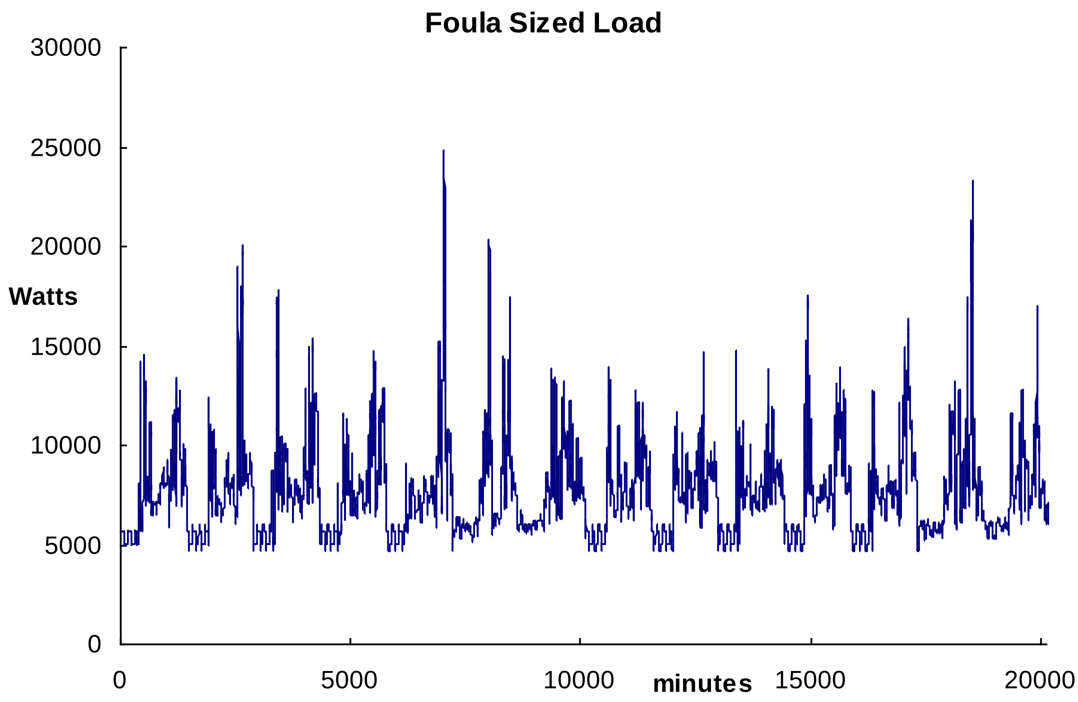


Figure 5.37 –Load profile for 14-day simulation run period

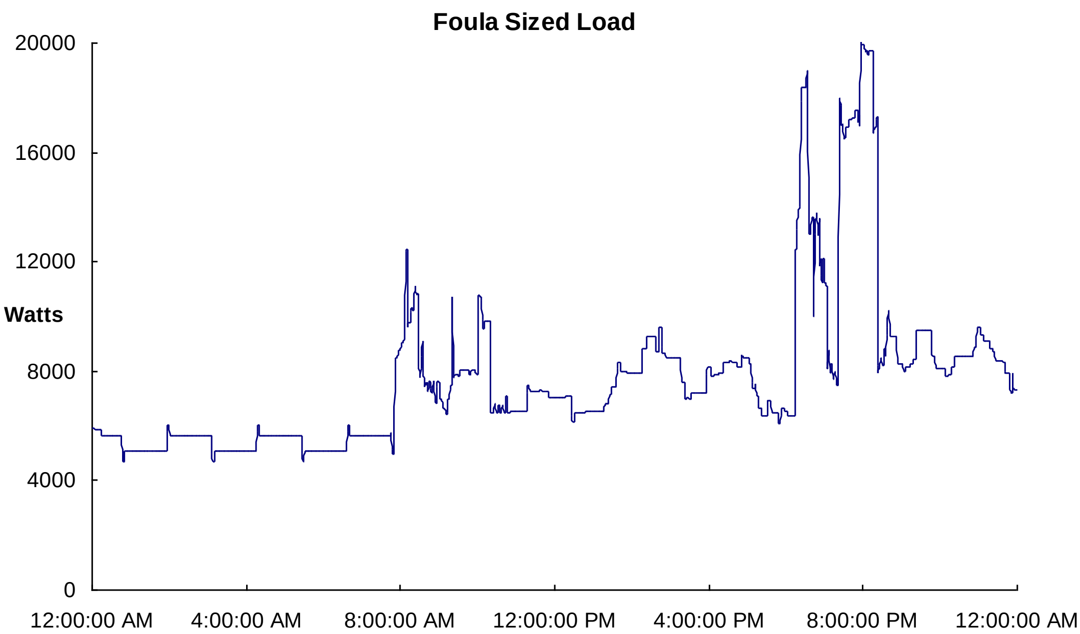


Figure 5.38 – Typical model daily load profile

Examining the load model results more closely, there are distinct phases throughout the day, Figure 5.39. During the early hours of the day until 8 am only the base load can be seen, which consists mainly of refrigeration compressor cycles and standby loads. The next phase is early morning when people wake up, turn lights on, make breakfast and get ready to go to work (6-9am). The next distinct phase is lunch time (post midday) with a few small peaks of meal making activity. The final phase is post work (after 6 in the evening), which is the highest peak load in the day, when people arrive home turn lights on, take care of domestic chores (washing, ironing, vacuuming and cook dinner) and relax or enjoy entertainment (TV, PC, Music, Books, Sports etc). Comparing the Foula sized load above with that for a typical UK household load (Figure 4.8 in section 4.1.2) the graphs can be seen to have a similar shape with the peaks and troughs in the same periods.

In order to get a more accurate picture of the load for the design community, detailed information should be gathered about the number of persons in individual household, appliances and employment, etc. The model Island has 32 people living in 13 houses with two other buildings (a School and an office). Foula, the case study Island community used for comparison, has a population of 31 people with 17 households.

The actual Island load demand shown in Chapter 3.5 can be seen to differ from that of the load model simulations. Foula has a higher base load and less pronounced phases with the morning load often being the highest in the day as opposed to the evening load. There are several possible reasons for their differences, including different household composition (house layout, number of occupants and devices) an over-estimate of the number of electronic/electrical equipment (given the likely reduced expendable wealth/high cost of electricity and limited supply) and work patterns are likely to be different from typical mainland jobs as well.

A number of different power system topologies (full Wind/PV/Diesel, Wind/Diesel, PV/Diesel hybrids and diesel only) were simulated to supply the load and all displayed strong fuel savings for the variable speed operation of the diesel generator. Variable speed operation produces a 43% fuel saving in the hybrid system compared with constant speed operation (9kW minimum loading).

For the Full hybrid system the results are tabulated below.

14 Day Results	***Kg***	***Kg/L***	***L***	***£ @ 50p/L***	***£/year***	***Savings***	***%***
Variable Speed (+ inverter loss)	460	0.85	541	£271	£7,055	£5,352	43
Constant DG	622	0.85	732	£366	£9,539	£2,868	23
Constant DG 9kW min	809	0.85	952	£476	£12,407	base	base

Table 19 – Power Balance hybrid model results

The model for the constant speed diesel generator has been simulated with two minimum load settings. The base case has a 32% of rated minimum loading, which equates to a 9kW minimum load, which is comparable to that specified by many manufacturers (Cummins is 30%). To meet this requirement, load dumps, long term energy storage or renewable generation shedding would need to be implemented. The other minimum load setting is 14% of rated or 4kW, which is the minimum load used for the variable speed generator, although smaller may be possible.

It can be seen that this minimum loading has a large influence on fuel use, especially in renewable hybrid systems, where there is a 23% reduction in fuel use between the same constant speed diesel generators with different minimum loading. The high penetration of renewable generation in the hybrid system dramatically reduces the power required by the diesel generator and therefore it spends more of the generating hours at minimum or low load. Even in the diesel generation only case, where loading will be above minimum for a greater proportion of time, there is still a 12% difference in fuel use between the different minimum loadings for the constant speed diesel genset, Table 5.9 below. Comparing the different forms of operation in the diesel only generation simulation, variable speed operation uses 28% less fuel over the 9kW minimum load constant speed operation.

14 Day Results	***Kg***	***Kg/L***	***L***	***£ @ 50p/L***	***£/year***	***Savings***	***%***
Variable Speed (+ inverter loss)	635	0.85	747	£373	£9,724	£3,729	28
Constant DG	768	0.85	904	£452	£11,784	£1,669	12
Constant DG 9kW min	877	0.85	1032	£516	£13,453	base	base

Table 20 - Power Balance diesel only model results

The fuel saving of a real system on Foula or the Shetland Islands could be expected to be greater than simulation results, given the higher mean wind speed found there compared with the data used in this simulation. The wind turbine has a large influence on potential fuel saving due to its high penetration.

5.4 Summary

In Chapter 5, the reasons for using modelling and simulation as a tool are explained. They allow prototype systems (ideas) to be quickly and cost-effectively assessed to a reasonable degree of certainty (accuracy). In addition, they allow tests that would, if carried out live, take days, months or years to be run in a fraction of the time. The behaviour of individual components or complete systems can be easily changed and the ensuing effect observed.

Modelling and simulation has mainly focused on the performance and fuel savings of the hybrid system. The proposed system topology of a common DC-link with individual generator control through DC/DC converters simulated.

Performance problems encountered with the variable speed hybrid system have been documented. The addition of a Supercapacitor power boost system has been demonstrated to greatly improve the variable speed hybrid systems stability under heavy load transients.

Sizing of the supercapacitor power boost system could be critical both in terms of overall system performance and economics. It is an extremely complex balancing act between cost and performance with every aspect of the hybrid power system and the load that it supplies potentially effecting sizing. As an example the size of the load change on the VSDG either by the loads on the grid or by sudden reductions in renewable power will influence the possible voltage drop. The Voltage Tolerance Curve of the most sensitive load on the grid may affect the maximum voltage drop allowed and therefore the size of the supercapacitor system needed. Due to the increased response time of the VSDG to load changes, the supercapacitor system is needed to help maintain system power balance during sudden load changes and help avoid a DC-link crash and subsequent grid blackout. There are many factors that determine the optimal size of the supercapacitor system.

They are:

- VSDG size
- VSDG speed setting
- Supercapacitor cost
- Maximum load steps/transients encountered
- Renewable power penetration (and type/inertia)
- Required DC-link/Grid stability (power quality)
- DC-link capacitance

The VSDG size can, for all intended purposes, be thought of as fixed because, it is sized to match the load requirement. In general the larger the VSDG the larger the supercapacitor system needed.

The most variable factors are the load transient, which is in relation to the loads on the mini-grid and the required grid stability, which may be set by loads on the grid or user defined.

High power low inertia renewable generation has the potential to be the most significant factor affecting supercapacitor system sizing, because it will be seen by the VSDG as a large fast load change.

The VSDG speed setting can be altered to increase the transient load response or fuel savings. Optimising the Supercapacitor system is a play off between system cost and potential fuel cost reductions. In essence, if the supercapacitors system allows the VSDG to run at the most fuel efficient point, and the cost of energy (COE) is minimised, then the system has been optimised.

The DC-link capacitance affects the rate of change in DC-link voltage under power imbalance and to a certain extent is predefined.

If we assume the maximum load step to be the maximum load, then the Supercapacitor system has to be sized so that it can supply the power deficit that occurs, otherwise the DC-link voltage will be quickly drained. This is a simple calculation of the voltage and current capabilities of the supercapacitor system. Dropping the supercapacitor system voltage to 80% of rated gives a more realistic initial operating condition.

Simulating the VSDG under full load acceleration allows the power and energy deficits to be determined. This, in turn, can be used to calculate the required supercapacitor system needed to maintain system stability.

Altering the speed set points changes the power and energy deficits and therefore the supercapacitor system needed along with the fuel consumption. The easiest way to increase the VSDG transient performance is to increase the minimum set speed. This negates some of the VSDG advantages over constant speed Gensets and increases the fuel consumption at lower powers.

Running a Simulation over a complete year to attain the amount of fuel used, allows the full life time economics of the complete system to be calculated.

It is evident from the results in the tables below that running the VSDG at it's most efficient speed set point and using the required supercapacitor system size to meet overall system performance criteria is the most economical over the lifetime of the system (20 years).

Example

28kW VSDG run at:

1000 rpm Supercapacitor system consists of 31 15V 58F modules

Giving a maximum power of $31 \times 15V \times 45A \approx 20kW$

1400 rpm Supercapacitor system consists of 25 15V 58F modules

Giving a maximum power of $25 \times 15V \times 45A \approx 17kW$

1800 rpm Supercapacitor system consists of 17 15V 58F modules

Giving a maximum power of $17 \times 15V \times 45A \approx 11.5kW$

All adequate to stop the DC-link crashing under a maximum load step of 28kWThe cost of one supercapacitor module is taken to be around £70. The rest of the supercapacitor system cost is associated with the DC/DC converter system.

Type	Supercapacitor system	Diesel Generator	Total Capital Cost	Annual Fuel cost
VSDG (1000rpm minimum)	£2,400	£14,000	£16,400	£9,970
VSDG (1400rpm minimum)	£2,000	£14,000	£16,000	£10,065
VSDG (1800rpm minimum)	£1,400	£14,000	£15,400	£10,491
Constant speed	£0	£7,000	£7,000	£12,083

Table 21

Interest and fuel cost added each year for the 20 year lifetime of the system.

Type	Interest		
	5%	7.5%	10%
VSDG (1000rpm minimum)	£373,182	£501,412	£681,363
VSDG (1400rpm minimum)	£375,262	£503,827	£684,113
VSDG (1800rpm minimum)	£387,756	£519,726	£704,476
Constant speed	£418,109	£552,985	£739,146

Table 22

The results show that the greatly increased initial cost of the complete system is paid back over the life time of the system even with high interest rates. The high annual cost of fuel means that the initial system cost only has a small effect on the overall life time costs. The cheapest system for all three interest rates is the VSDG that is able to run at an idle speed of 1000 rpm and therefore follow the optimal efficiency operation point for more of the power range due to the increase supercapacitor system power. The most expensive system for all three interest rates over the 20 year lifetime is the constant speed generator with higher annual fuel costs due to the inefficient operation at part load. The increased cost of the VSDG and Supercapacitor system pays for itself within 7 years for all three of the interest rates calculated.

A detailed load model and 14 days of real renewable resource data have been implemented in the complete hybrid system model, so that the long-term operation could be assessed. The system operated satisfactorily and strong fuel savings have also been calculated.

6 Wind/PV-Diesel Emulation

Wind/PV-Diesel emulation has been undertaken on low power electro mechanical test rigs. Due to the complex interactions occurring within the fully integrated variable speed hybrid system, the best way to verify compatibility of components and control stability is through experimentation. Two different test benches have been used during the experimentation, one at the University of Cassino, Italy and the other at the University of Edinburgh, UK. At the time, access to a VSDG was not available and hence experimentation was conducted on a low power test rig in order to demonstrate the basic principles of the control in a hybrid renewable energy system.

The two different experimental systems, although different in their topology, share some common parts. Both supply variable resistive loads with DC power and utilise the Maxwell Supercapacitor modules. The main role of the supercapacitors is to provide the increased power demand, while the emulated engine increases its speed to the correct operating point. The Supercapacitor system comprises of up to five 15V 58F Maxwell Supercapacitors in series (75V 11.6F), although it was found to run adequately on only three in Edinburgh.

The control and monitoring of the system was accomplished using dSPACE ControlDesk. A control model is constructed in Matlab Simulink using real time dSPACE interface blocks as the models inputs and outputs. This is then loaded onto the dedicated dSPACE processor, which can be controlled through the ControlDesk software. In the ControlDesk programme, a customized layout is created, displaying as much of the available model data as required. An example of this is displayed in Figure 6.1. Some model parameters can also be changed in situ, allowing control gains to be changed and manual control to be achieved.

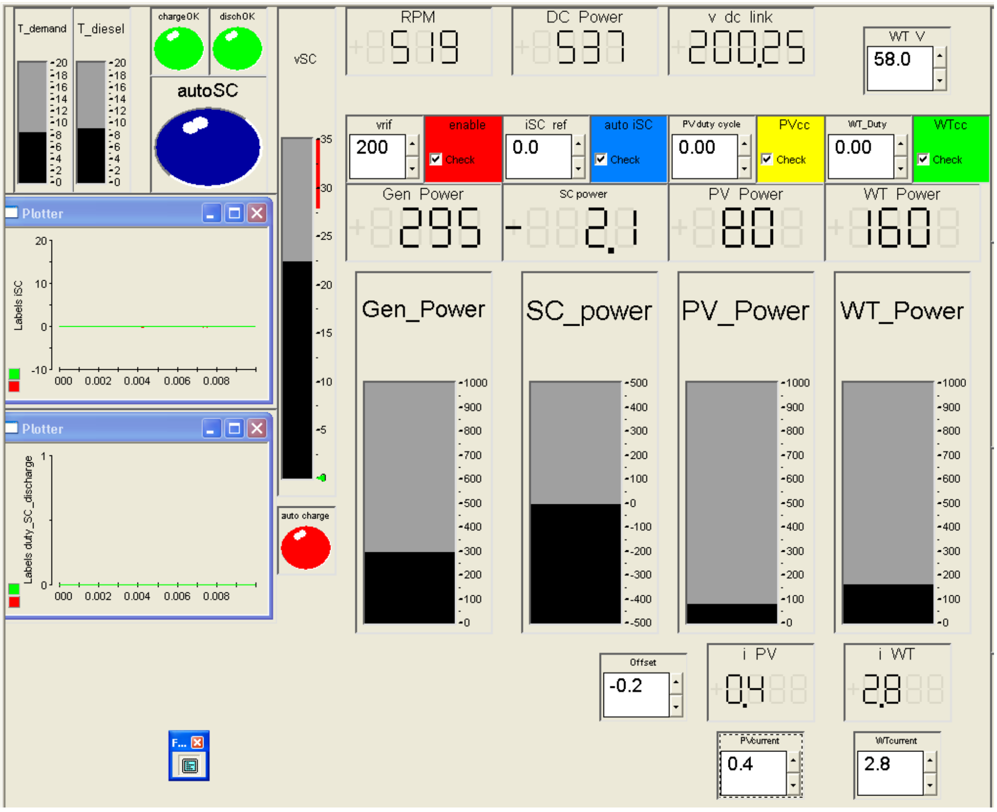


Figure 6.1– dSPACE ControlDesk screen print

The control signals and system measurements are connected to the dSPACE hardware board as shown in Figure 6.2 and can be either digital or analogue signals.

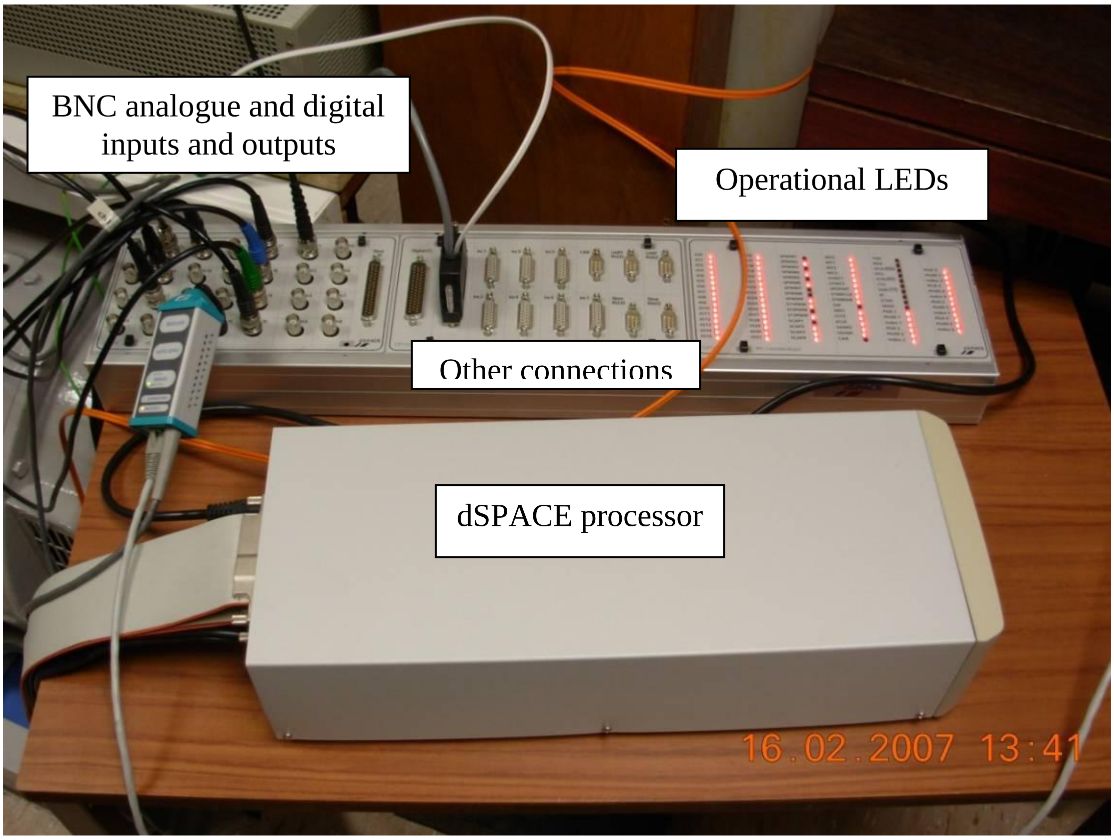


Figure 6.2 – dSPACE hardware

In this chapter, the different experimental setups are described. The performance of the systems is assessed and some of the problems encountered and their solutions are discussed.

6.1 Testing at the University of Cassino, Italy

A joint project between the University of Edinburgh and the University of Cassino was funded by the British Council Italy-UK Scientific Partner Programme, in order to enable a staff/student exchange for a number of weeks on two separate occasions. This allowed access to the high tech facilities and equipment at the University of Cassino and helped accelerate the initial experimentation. PV panels were available for connection to the test rig at the University of Cassino and have been used as the renewable part of the hybrid. PV panels have a high probability of being used in an off grid hybrid power system and it was therefore considered beneficial to test them.

6.1.1 Components & testing arrangement

The test rig in Cassino consisted of a SIMODRIVE permanent magnet motor (PMM) and an axial flux permanent magnet generator (PMG) and 1kW of Eurosolare PL800 Photovoltaic panels. During the first visit, battery energy storage was used and on the second visit the Supercapacitors were used. A block diagram of the experimental system and the associated power converters are shown in Figure 6.3.

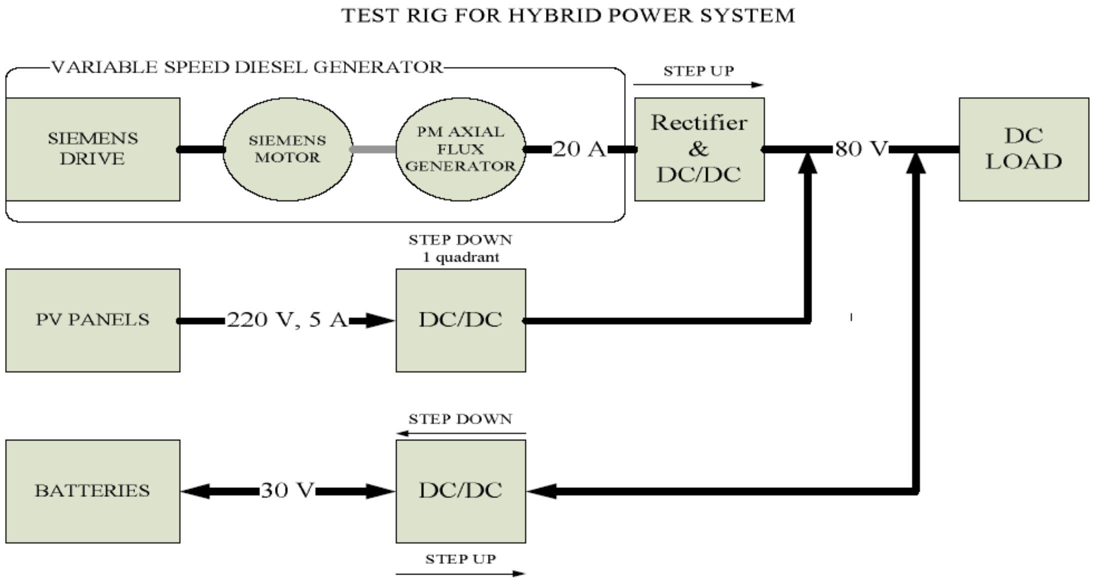


Figure 6.3– Cassino test rig

The SIMODRIVE torque controlled PMM used to drive the axial flux PMG (Figure 6.4) was used to emulate the variable speed diesel generator. The PMM is modelled in the control system so that it represents the diesel engine. This is executed by a simple transfer function and torque limitation scheme as used in the VSDG model in Section 5.2.2. The power from the three phase AC PMG is rectified (Figure 6.6) to varying voltage DC and then converted to the DC link constant voltage through a step-up converter.

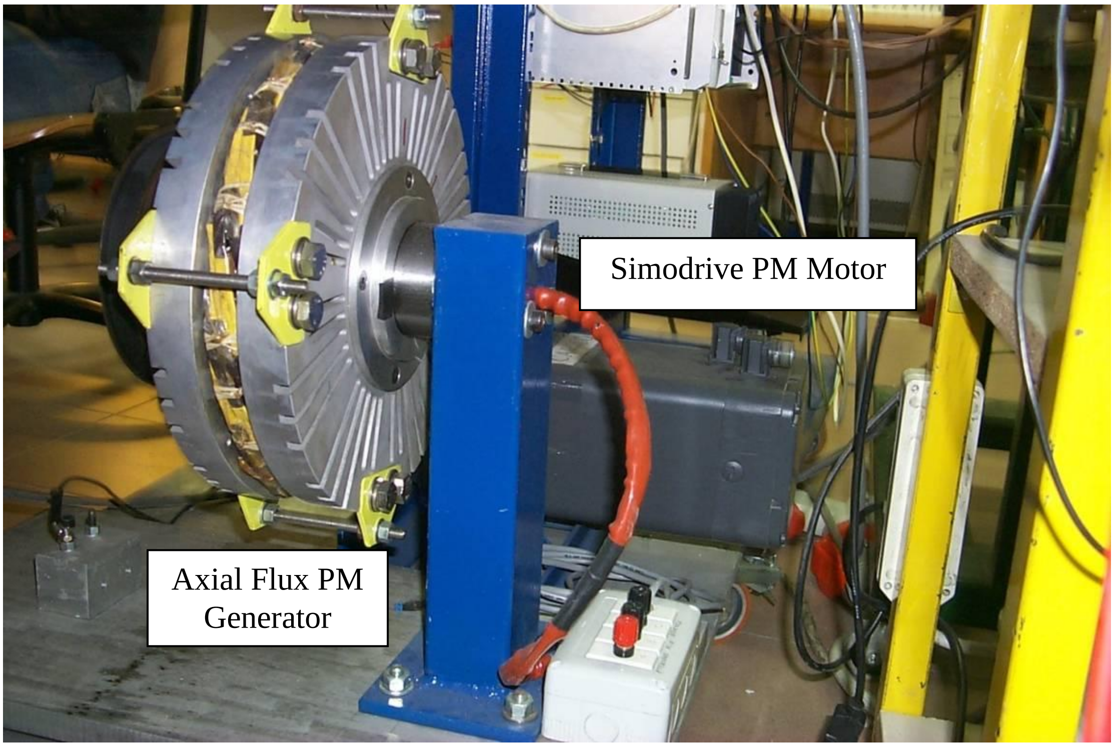


Figure 6.4 - Simodrive 611 control system 1.2kW PMG

Figure 6.5 shows the battery bank, the inductor used for the PV and the variable resistor used as the main load.

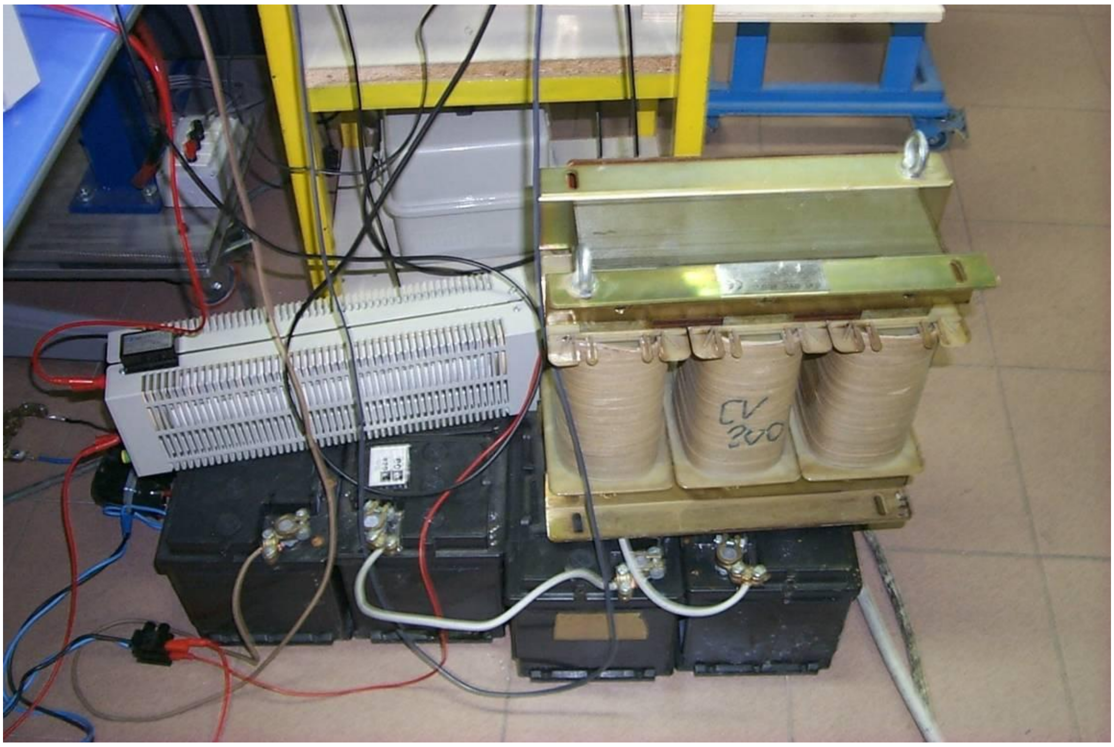


Figure 6.5 – Batteries, inductor and variable resistor used in Cassino

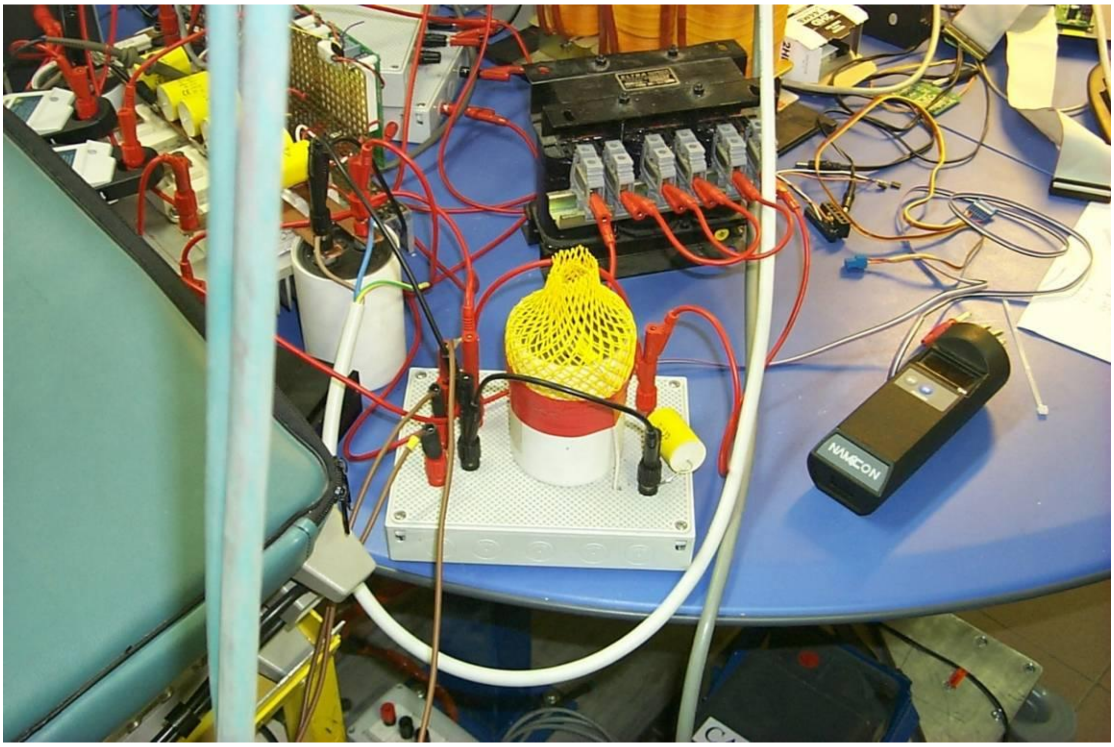


Figure 6.6 – Hybrid system rectifier with built in DC link capacitor

During testing of the emulated VSDG (PMM & PMG), an oscillation in the generator speed appeared at constant load. Initially, this had been accredited to the speed controller and then the belt drive had been suspected, but the cause turn out to be a broken encoder.

Due to the problem with the speed encoder of the above generator and time constraints on a possible repair, a different generator, shown below in Figure 6.7, was implemented. This generator was much harder to control due to its very low inertia compared with the previous larger diameter axial flux permanent magnet generator and so all the control values had to be fine tuned again in order to obtain stable control.

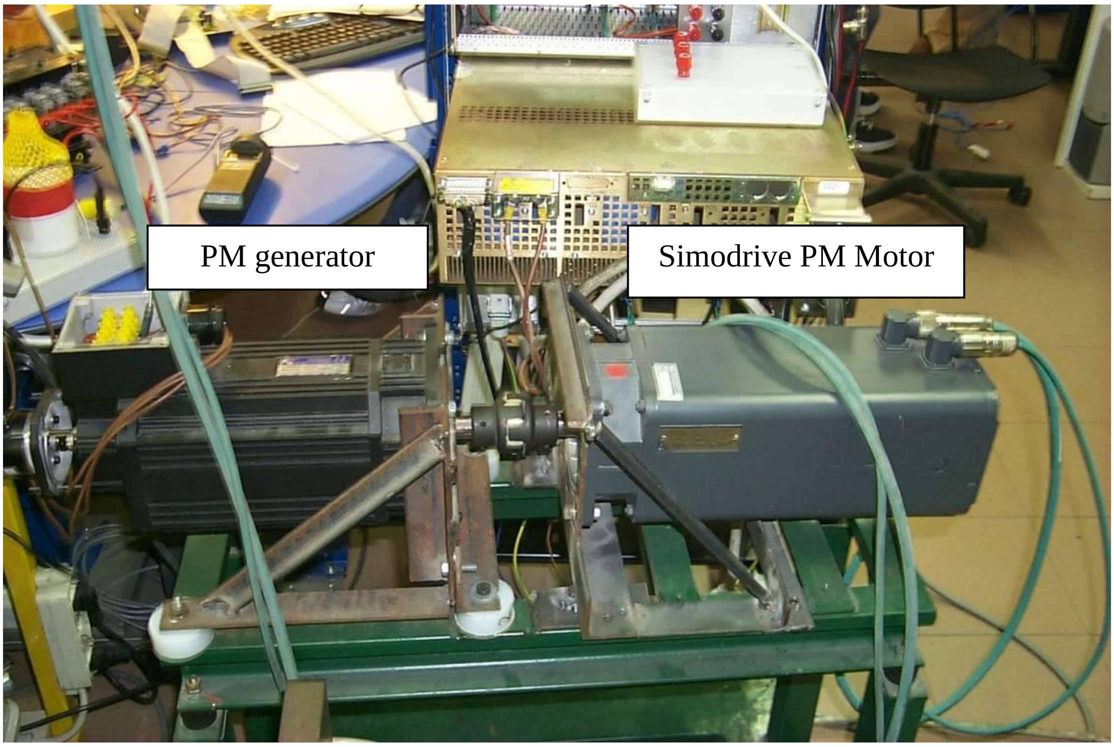


Figure 6.7 – Replacement motor generator set up 1kW

Figure 6.8 displays the electrical and electronic component layout and the placement of voltage and current measurement taps for the test rig in Cassino. The power electronic switches and diodes highlighted are ones not in use in normal operation.

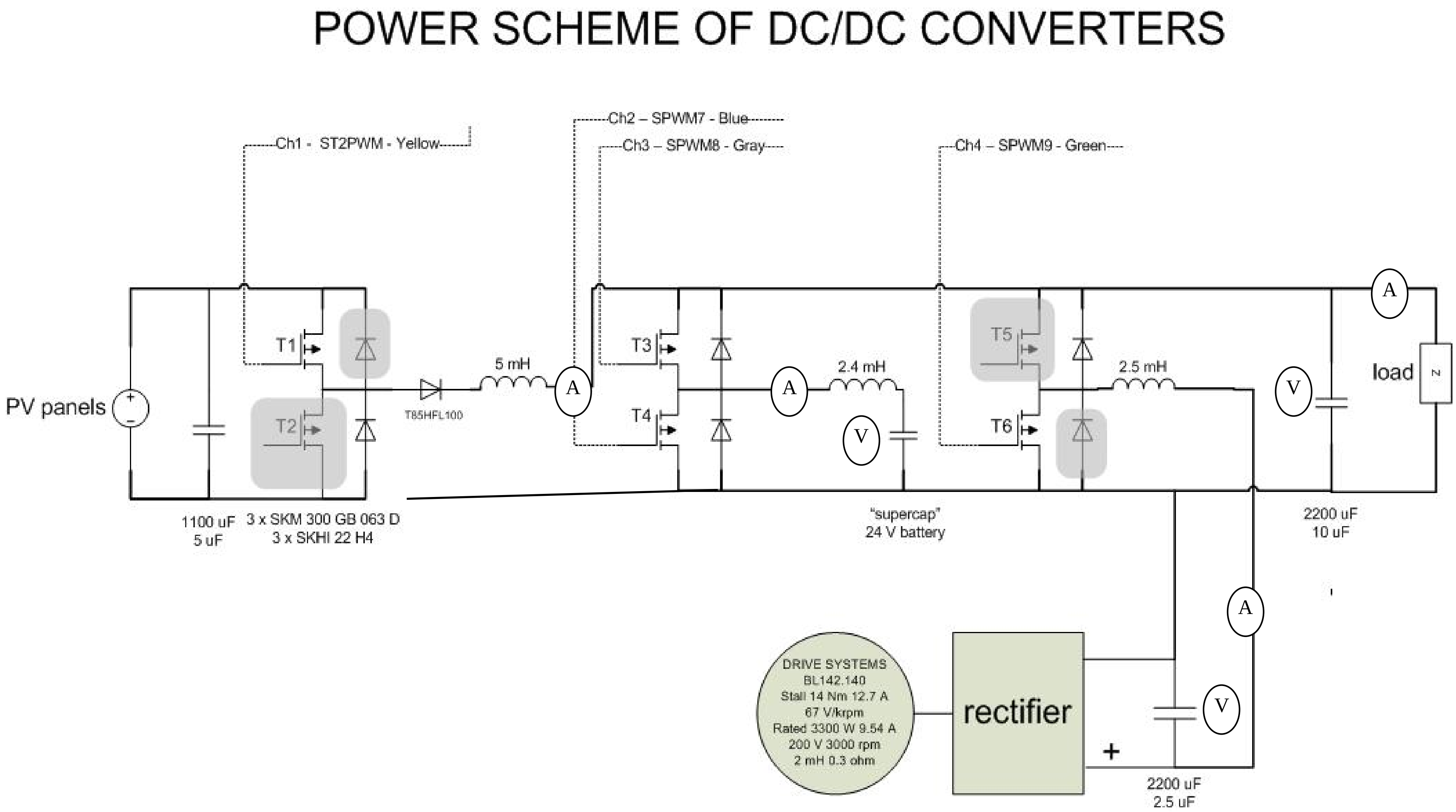


Figure 6.8 – Cassino power electronic layout

Each of the DC/DC converters uses a dual gate IGBT module that is controlled through a driver module from the dSPACE output PWM interface. The duty cycle is current controlled using the control programme specified in Matlab Simulink and operates on a constant carrier frequency of 20 kHz. The Supercapacitor converter is the only converter to utilise both IGBT switches, because it has bi-directional power flow, as shown in Figure 6.9 below. The voltage is stepped down when charging and stepped up when discharging.

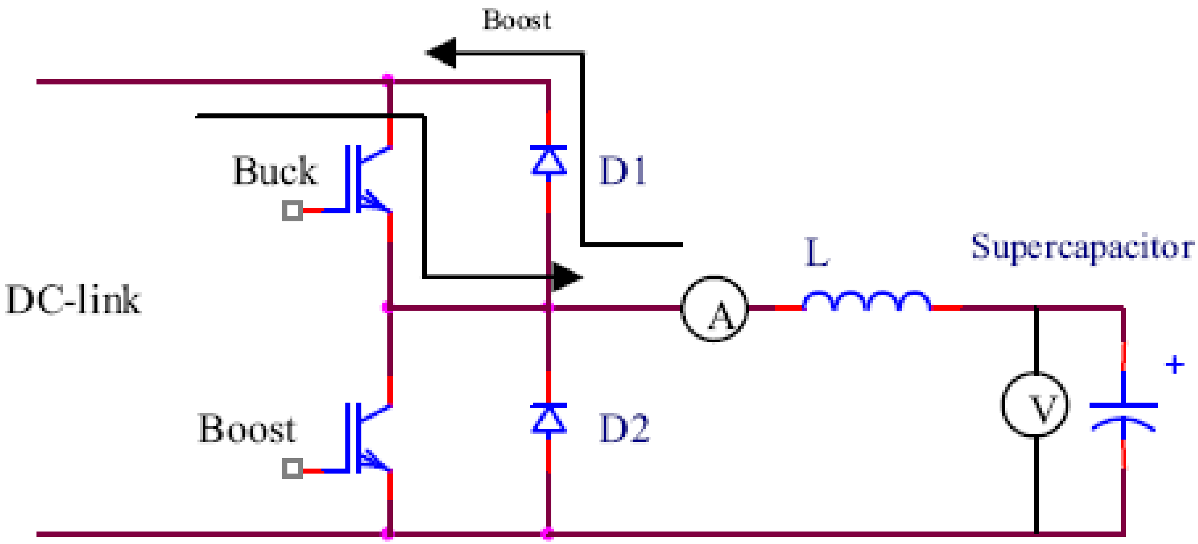


Figure 6.9 – Supercapacitor bi-directional DC/DC converter schematic

The PV generation is connected to the DC link through a step down (buck) converter, because it generates higher voltages than the DC link. The PMG uses a step up (boost) converter and the generator maximum rotational speed has been limited to ensure generator voltage output does not exceed the DC link voltage at higher rotational speeds.

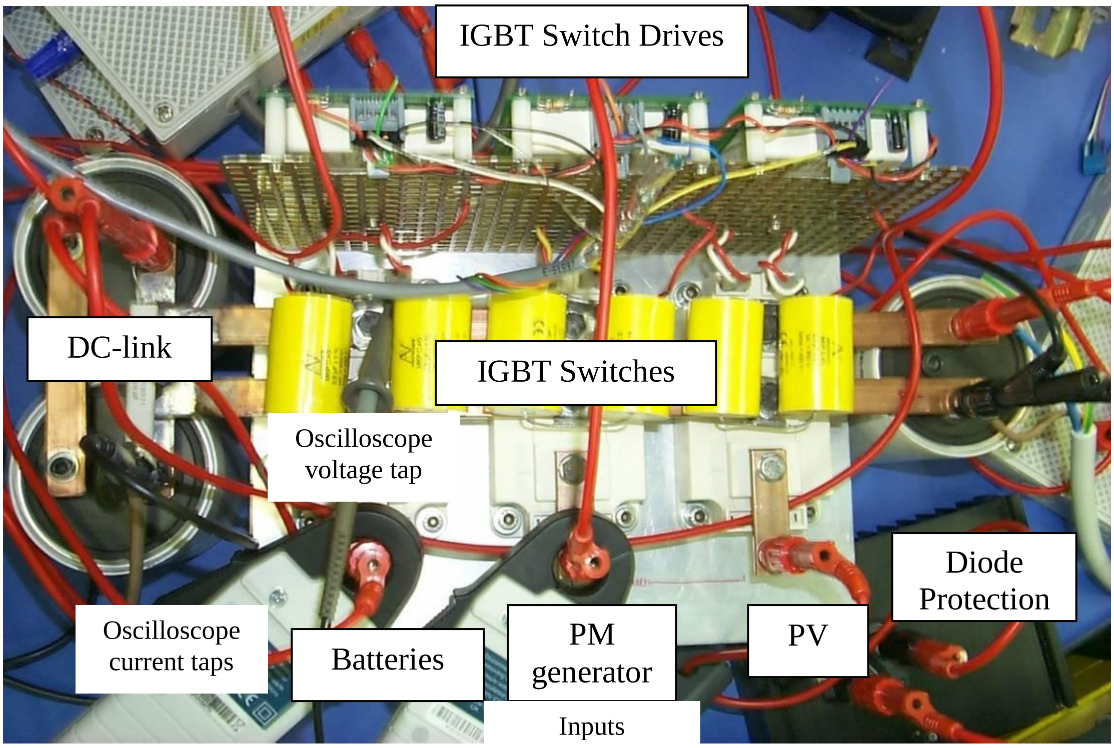


Figure 6.10 – System power electronics and DC link connections picture

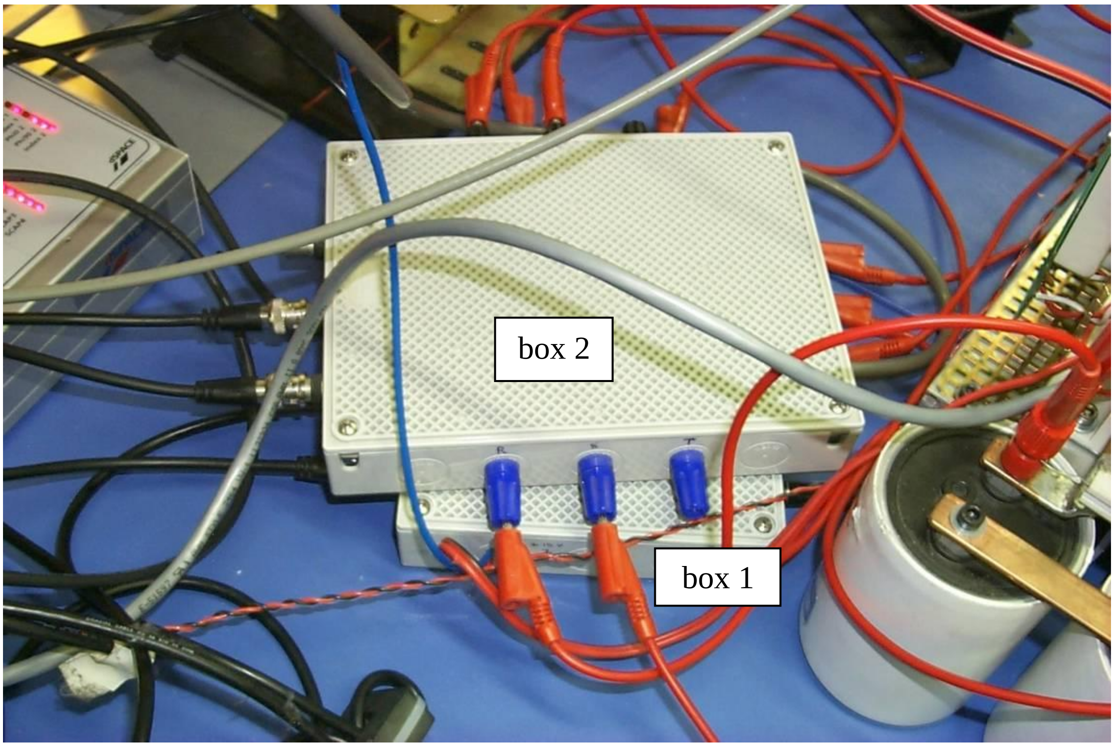


Figure 6.11 – Current and Voltage measurement boxes

Three voltage and four current measurements were available (box 1: 3 voltage, 1 current; box 2: 3 current, shown in Figure 6.11) for input in to dSPACE. The PV used one current measurement on the low voltage (DC link) side of the DC/DC buck converter. DC link voltage measurement has been taken across the DC link capacitors with the current measurement placed in series with the load. The variable speed PM generator measurements occur on the low voltage (pre DC link) side with voltage measured across the rectifier filter capacitor and current reading taken from the positive wire to the DC/DC boost converter. The voltage across the Supercapacitors is measured and the current measurement is taken between the DC/DC converter and the inductor, all of which are illustrated in Figure 6.8. The rotational speed of the PM motor/generator has also been used in the control scheme.

An overview of the complete control scheme implemented in Cassino is detailed below and illustrated in Figure 6.13. Batteries have been used as a supercapacitor substitute during the first visit.

The duty cycle value of the PV step down converter can be controlled in two different ways depending on the system setting. When there is enough load demand to ensure PV power does not exceed the Load needed, the duty cycle is controlled to achieve maximum power using a simple Maximum Power Point Tracker (MPPT). The MPPT operates by assuming the DC link voltage is constant (or stable) therefore the current through the output inductor is directly proportional to the power being produced.

The control algorithm searches for the maximum power by perturbing the duty cycle and observing the change in current. If the change in duty cycle produces an increase in power (current) the search will continue in the same direction (increasing or decreasing duty); otherwise, the control will reverse the duty cycle perturbation and check the change in power (current) again. The MPPT should find a settling point close to the knee of the curve in Figure 6.12 around the maximum power point, which is illustrated by the black line in the graph.

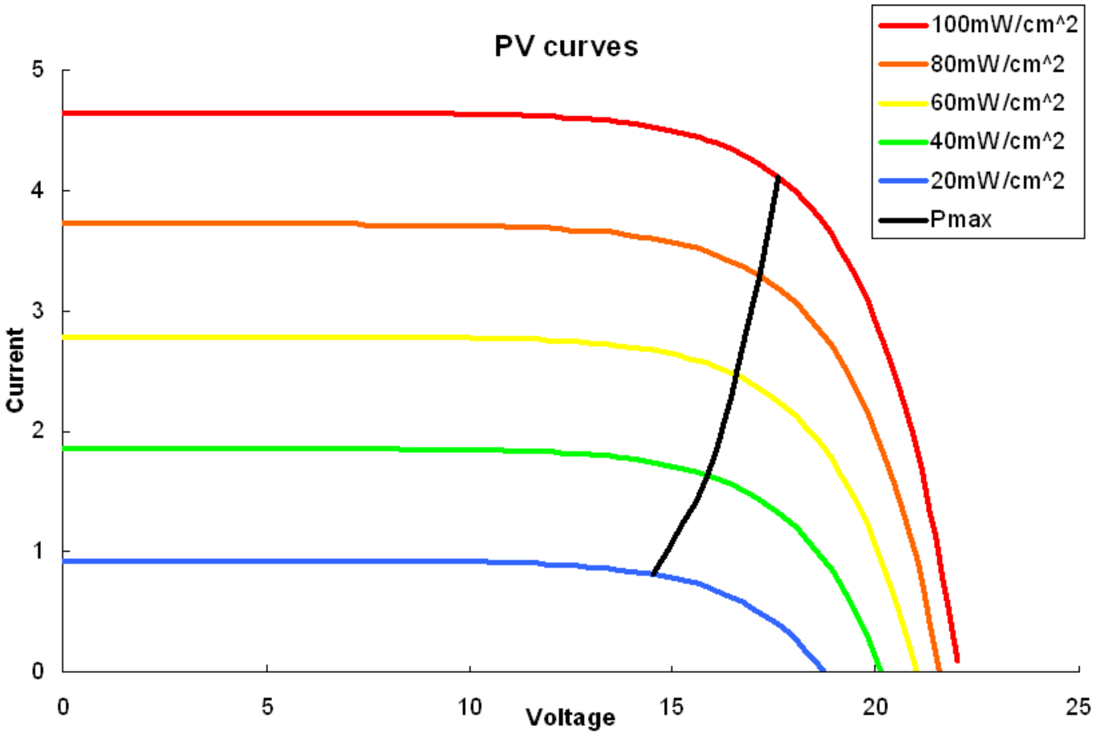


Figure 6.12 – PV voltage current curves

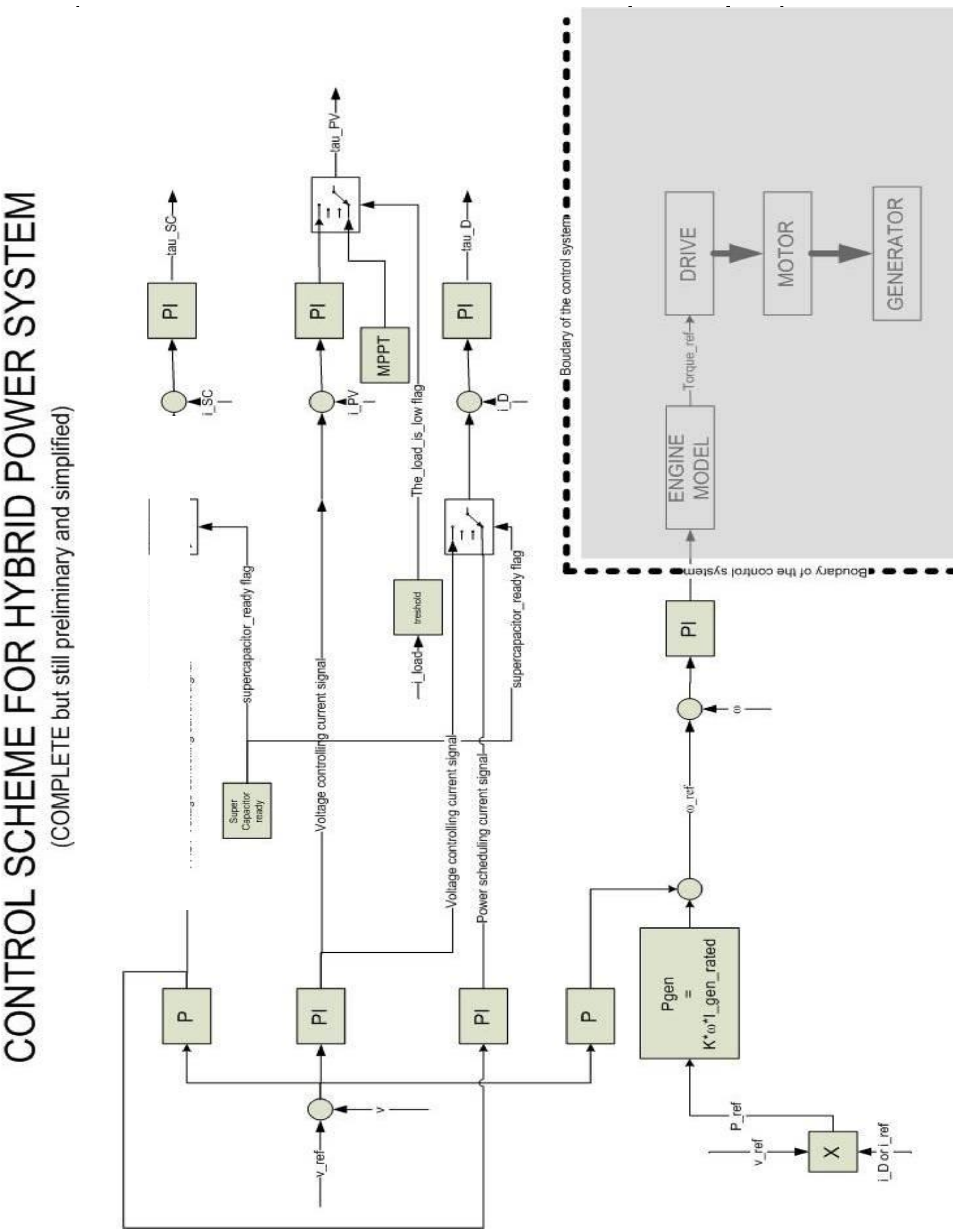


Figure 6.13 – Hybrid system control scheme

The MPPT has been tested and found to achieve at least 85% of the maximum power through a manual sweep of the duty cycle. This is subject to errors, because of the fluctuating nature of the solar radiation and the lack of equipment to measure it. The second mode of operation for the PV duty cycle is to ensure DC link stability when the majority of the power from the hybrid system is delivered by the PV (diesel engine low load). When this occurs, the system is no longer controlled to produce maximum power; instead, the duty cycle is controlled using two nested voltage and current PI control loops to maintain DC link voltage as shown in Figure 6.13.

The emulated VSDG, contained within the boundary of the control system dashed lines in Figure 6.13, is controlled for power through motor torque (throttle angle) and generator current. The VSDG speed reference, ω_ref is determined through the sum of the power-proportional speed term and a proportional term of the DC link voltage error. A PI controller imposes the determined speed. The power-proportional speed term produces the majority of the speed reference term under normal operating conditions and is represented by the linear relationship shown below.

$$P_{GEN} = K \times \omega \times I_{GEN\_rated} \quad \textbf{(6.1)}$$

$$\omega = \frac{P_{GEN}}{K \times I_{GEN}} \quad \textbf{(6.2)}$$

The power required is calculated by the DC link voltage reference

$$P_{REF} = V_{DC\_ref} \times I_D \quad \textbf{(6.3)}$$

The scheme for the generator current control changes depending on the supercapacitors state of charge, which is just a measure of voltage (unlike in batteries) and is represented by the super capacitor ready subsystem box in Figure 6.13.

If the supercapacitors are not ready to operate, then voltage control becomes the sole responsibility of the VSDG assuming high load and PV operating in MPPT mode. In this state, the voltage control is operated by an external PI loop acting on the internal current PI loop of the diesel unit step up converter.

If the Supercapacitors are ready to operate, then voltage control becomes the joint responsibility of the VSDG and Supercapacitors, again assuming high load and PV operating in MPPT mode. In this state, the voltage control would be operated by an external proportional gain acting on the internal current PI loop of the supercapacitors converter control. The current reference of the SC control, output of top proportional control in Figure 6.14, is used as the input to the external PI loop (mainly integral) acting on the internal current PI loop of the diesel unit step up converter.

The supercapacitor control model used and developed in Edinburgh was implemented during the second visit to Cassino. Alterations to the PM generator current control were made to slow down the response to a purely integral control, which allowed the supercapacitors to supply the initial fast current change.

Changes were also made to the auto control of the supercapacitors at turn on. Previously, the switching on of the auto control caused a large discharge as the PM generator current control switched from normal PI control to solely integral control, which would start from zero. To alleviate this problem, the integrator was loaded with the present generator current control value upon switch on. This improved the system stability during switch over dramatically.

6.1.2 Experimental Tests & Results

Initially, the experiment was set up in steady state initially with the generator supplying a constant resistive load. The system was then subjected to a step load change and the responses are plotted. The Figures below show the DC link voltage (bottom plot) and current (1V/A) responses with and without batteries. The fast current response is that of the batteries and the slow current (top plot) is that of the generator.

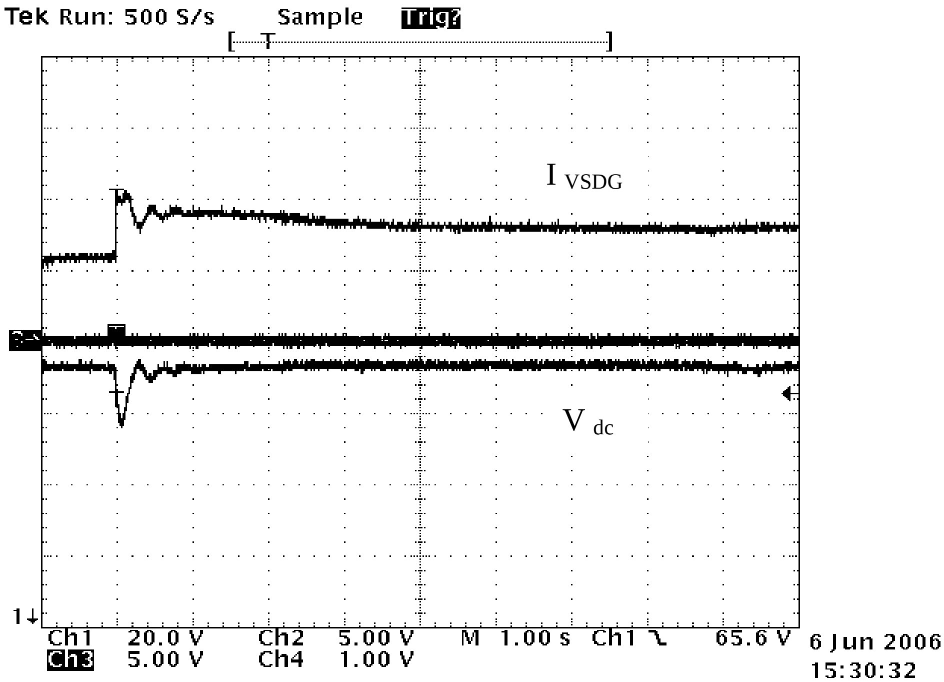


Figure 6.14– VSDG load step response

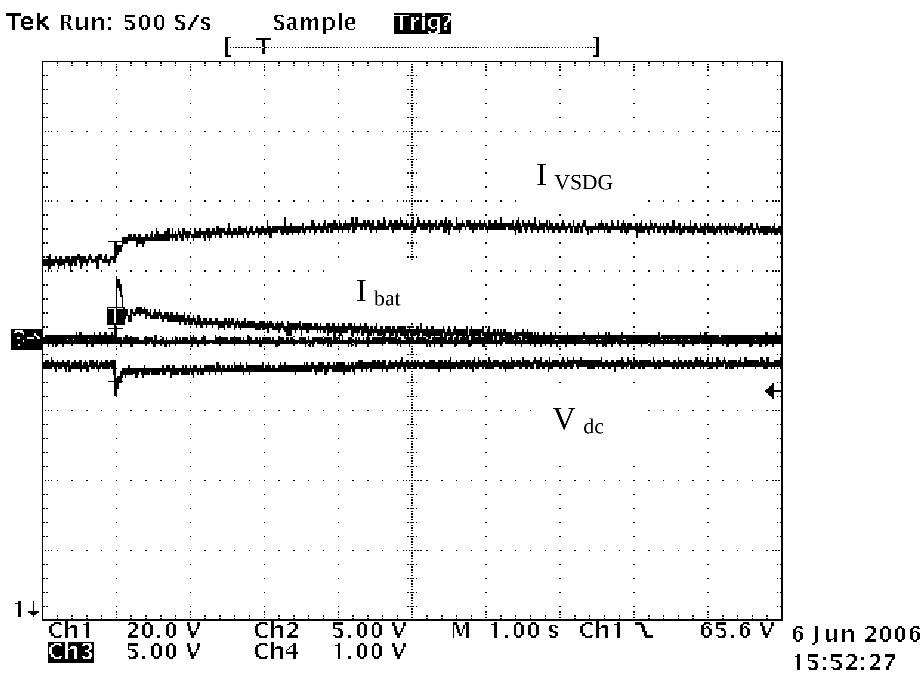


Figure 6.15 - VSDG plus Batteries load step response

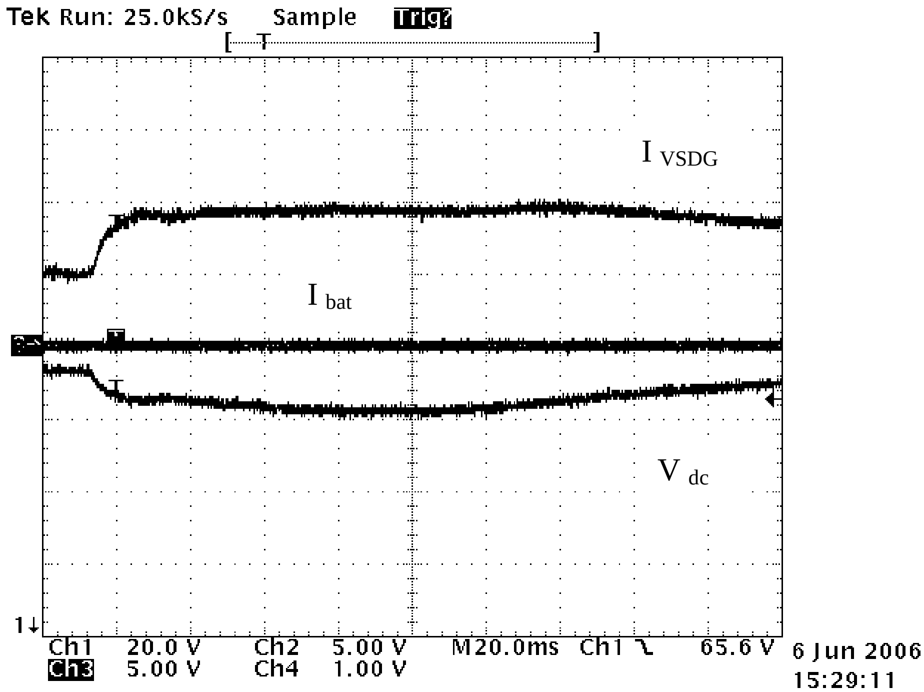


Figure 6.16 – Zoomed in VSDG load step response

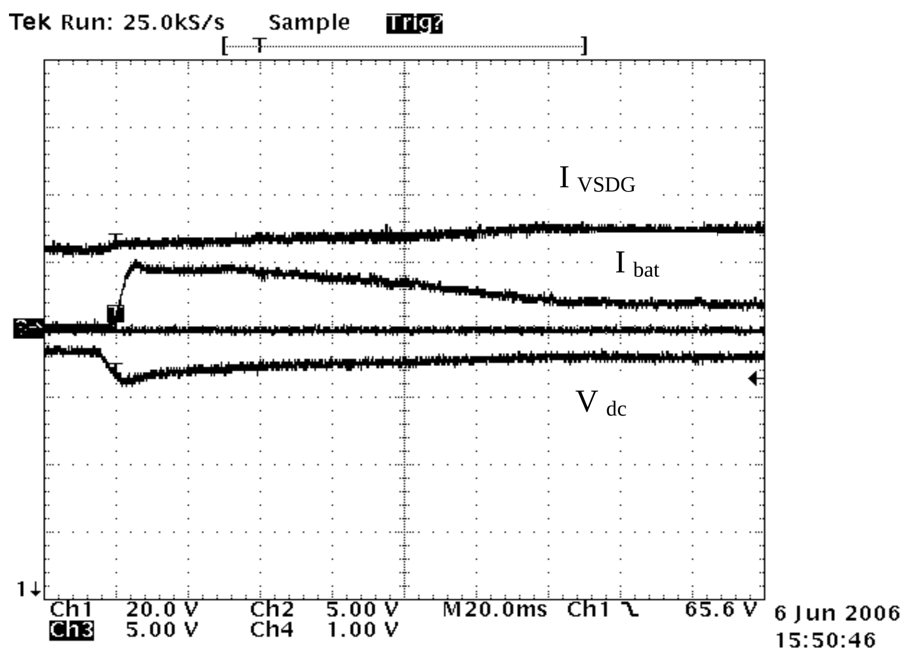


Figure 6.17 - Zoomed in VSDG plus Batteries load step response

It is clear the batteries reduced the voltage deviation and time for which it's present and therefore improve the system response.

The test above was then repeated, this time with the inclusion of PV power. Figures 6.18 to 6.21 relate to a load step occurring when the PV MPPT is active: Fig. 6.18 and Fig.6.19 without battery, Figs. 6.20 and 6.21 with.

The plots in the Figures are top to bottom: VSDG current, PV current, Battery current (zero for without batteries) and DC link voltage (Ch1 20V/division).

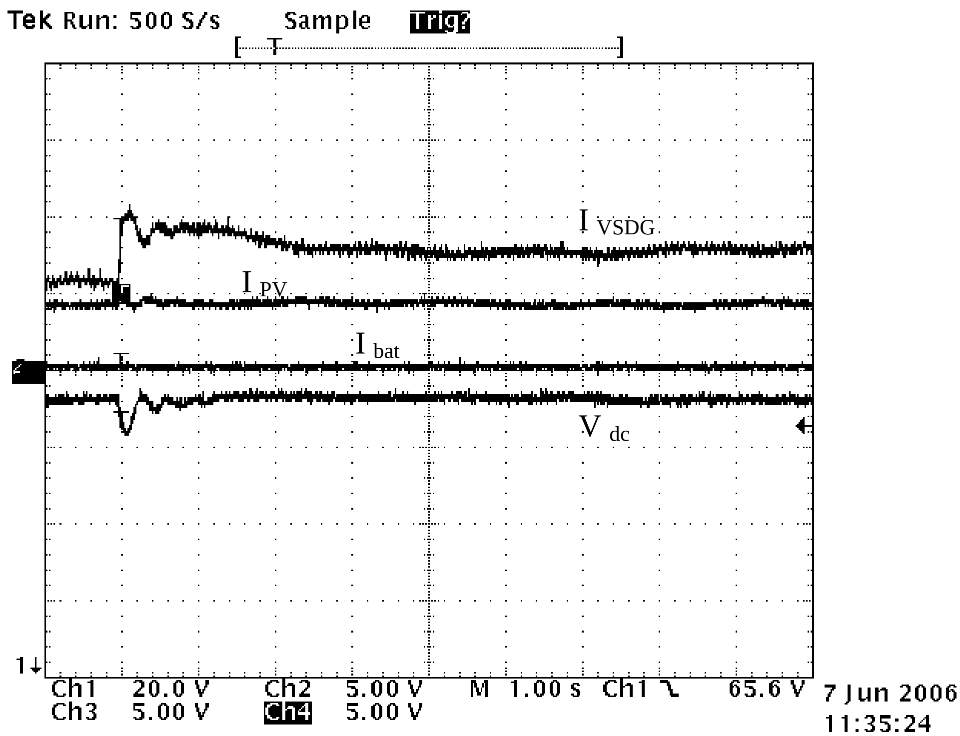


Figure 6.18 - Load step with MPPT PV operation and without batteries

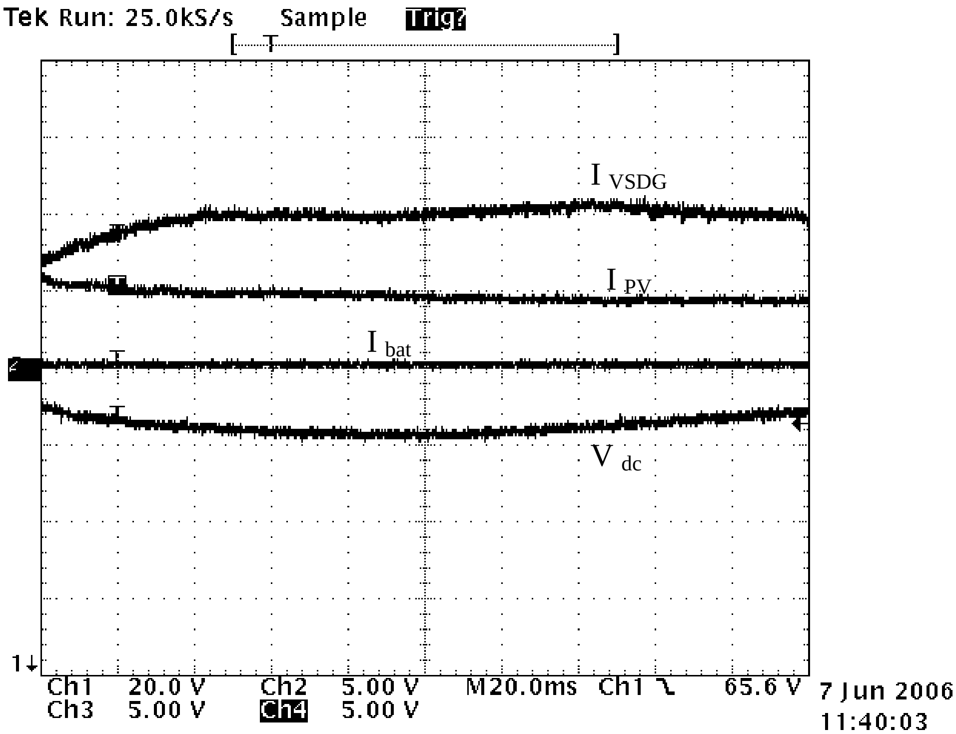


Figure 6.19 - Zoomed in load step with MPPT PV operation and without batteries

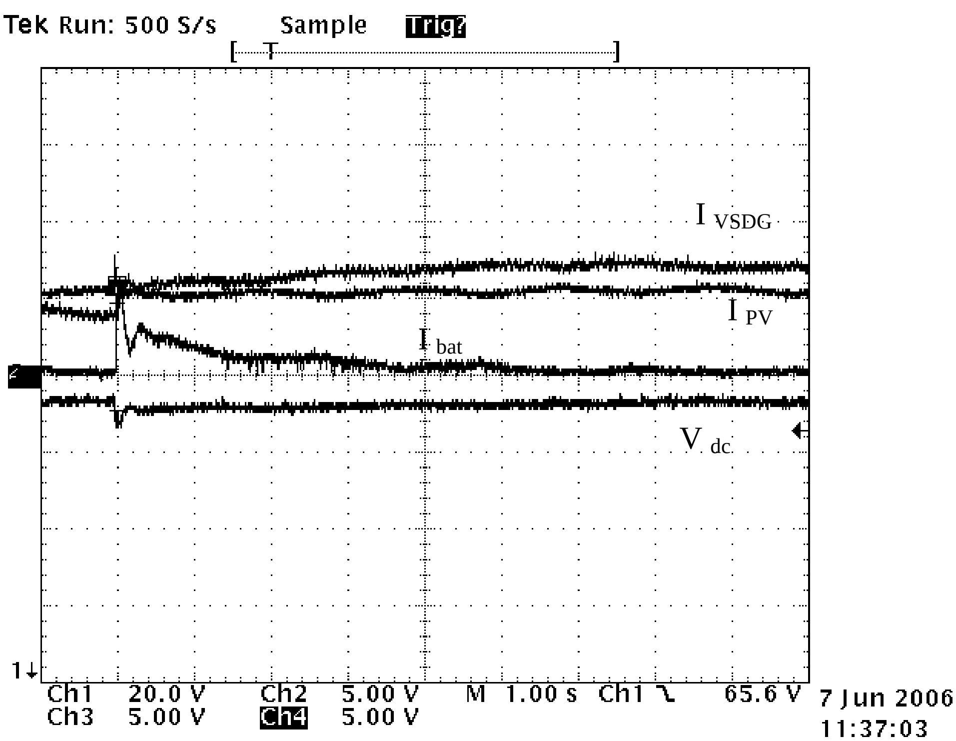


Figure 6.20 - Load step with MPPT PV operation and with batteries

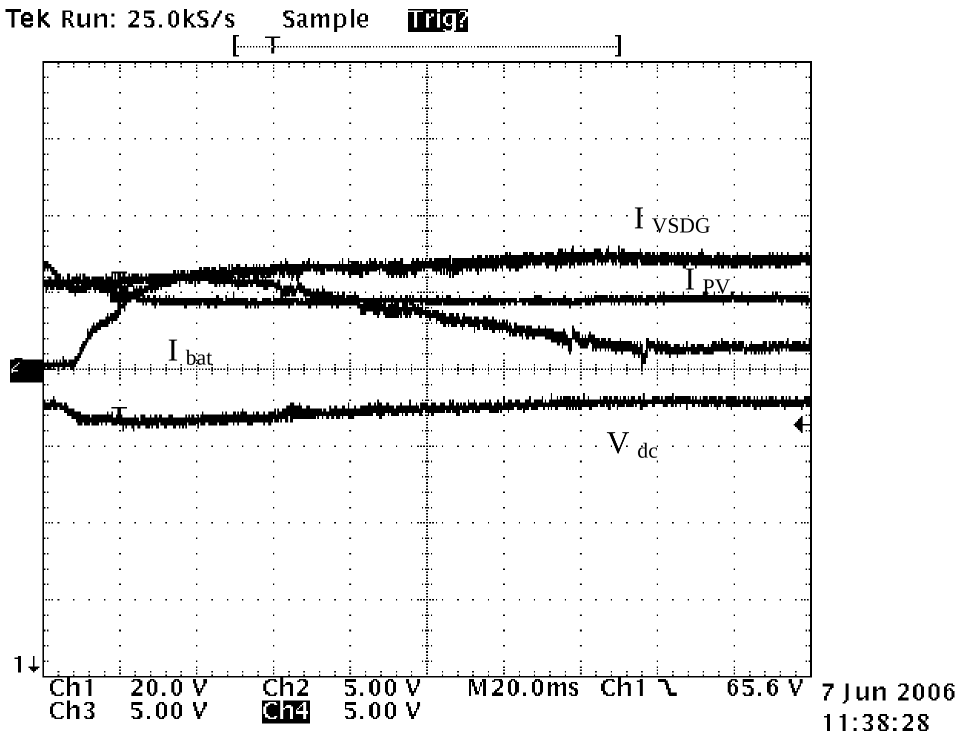


Figure 6.21 – Zoomed in load step with MPPT PV operation and with batteries

The presence of the PV power does not introduce any instability into the system.

To assess the stability of the PV MPPT further, Figures 6.22 to 6.24 plot the response of the Battery-VSDG-PV hybrid system during steady state conditions (constant load).

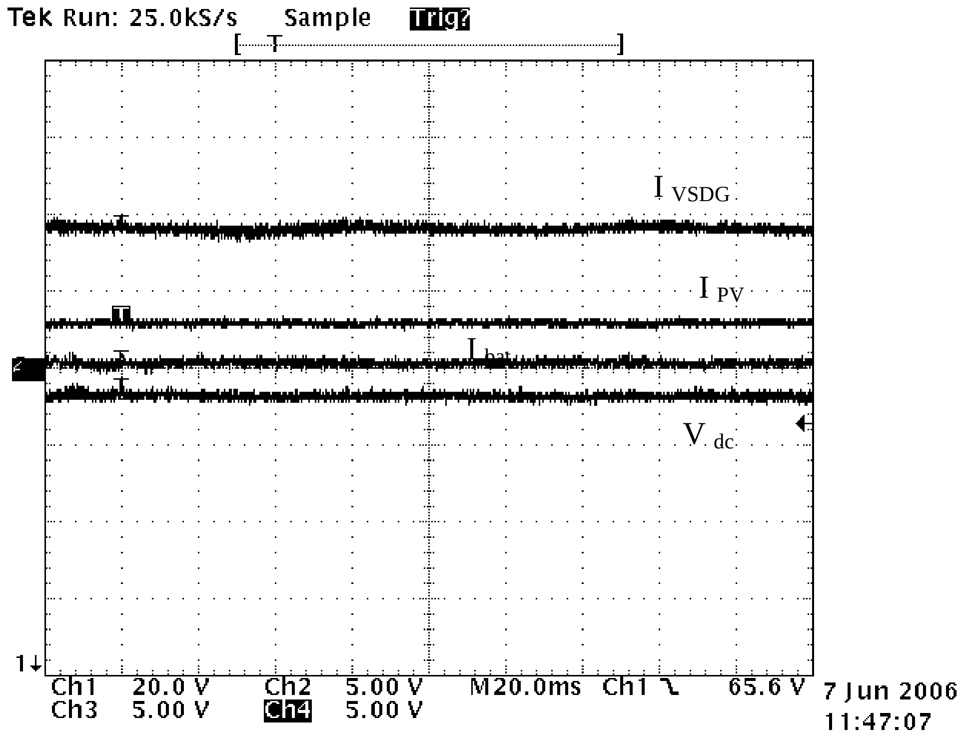


Figure 6.22 - PV MPPT steady state with batteries

t = 20ms div, top to bottom: I_{VSDG}, I_{PV}, I_{bat}, V_{dc}

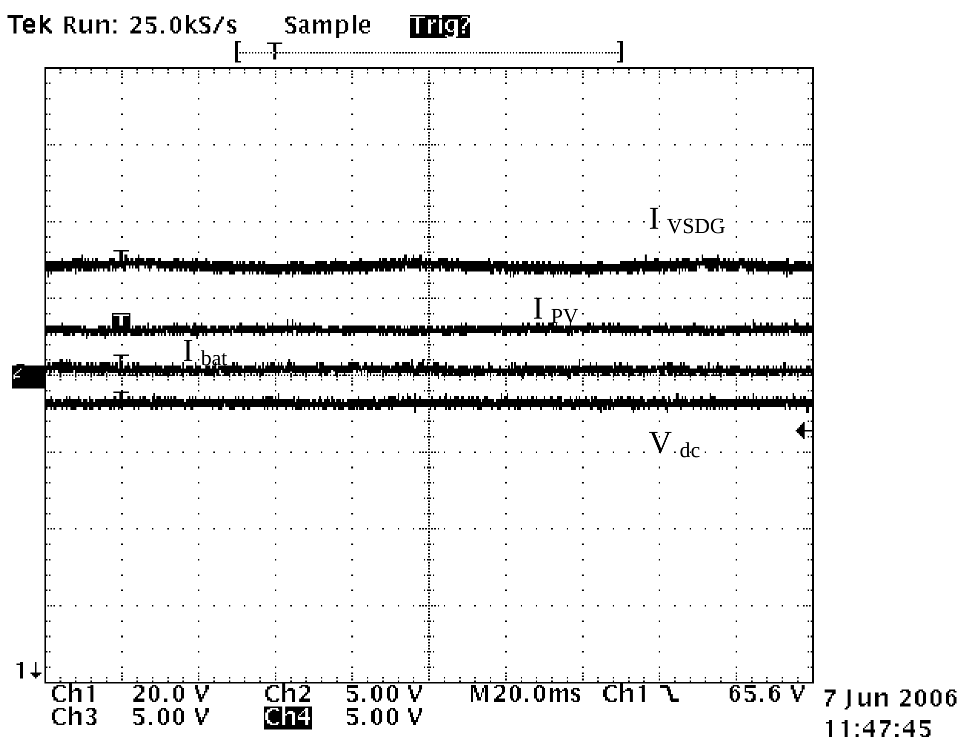


Figure 6.23 - PV MPPT steady state with batteries

t = 20ms div, top to bottom: I_{VSDG}, I_{PV}, I_{bat}, V_{dc}

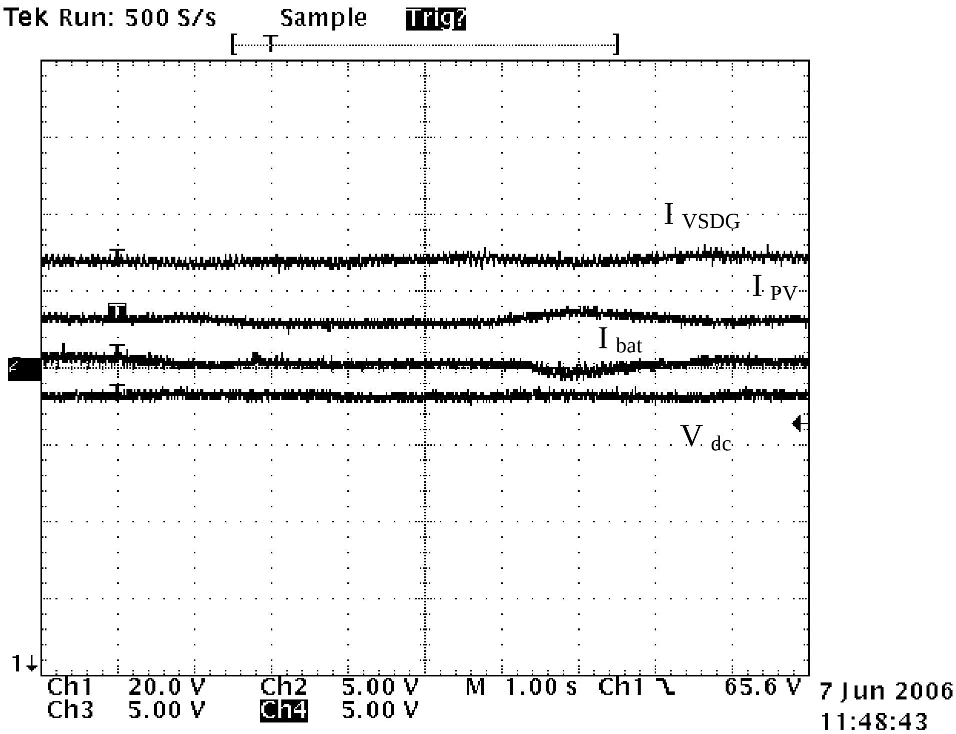


Figure 6.24 - PV MPPT steady state with batteries
t = 1s div, top to bottom: I_{VSDG}, I_{PV}, I_{bat}, V_{dc}

As can be seen, the system remains stable with no unnecessary oscillations occurring between the devices.

To assess the search operation of the MPPT both with and without batteries, the PV MPPT is initially turned off, so no power is being supplied from the PV panels and the rest of the system (VSDG or VSDG plus Batteries) is placed in a steady state and the MPPT is initiated. Figures 6.25 and 6.26 show the PV MPPT searching for the optimum operating point and the impact of this on the system.

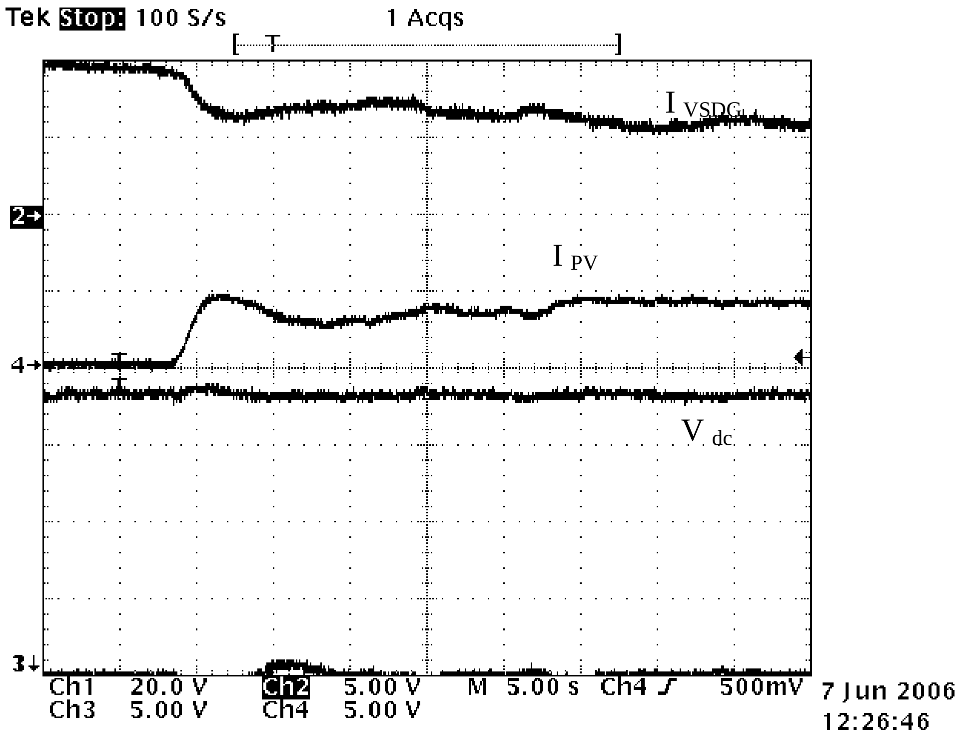


Figure 6.25 - PV MPPT searching operation with batteries

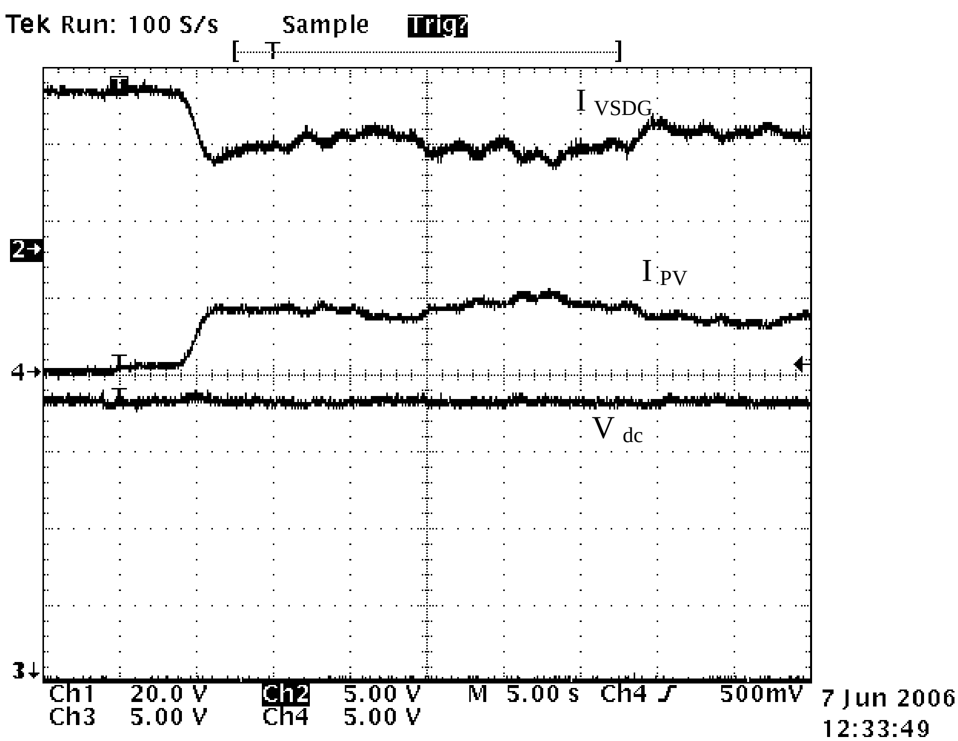


Figure 6.26 - PV MPPT searching operation without batteries

The results of this test show the improved stability of the system with batteries and the quicker response of the MPPT

During the second visit, the tests were conducted again, using 5 supercapacitor modules in place of the battery storage. Some of the tests were rerun to assess their performance and to compare these with batteries.

The first test carried out was a step load response. Figure 6.27 shows the DC-link voltage, diesel generator and supercapacitor response to the step load change. All results are in true voltage and current readings.

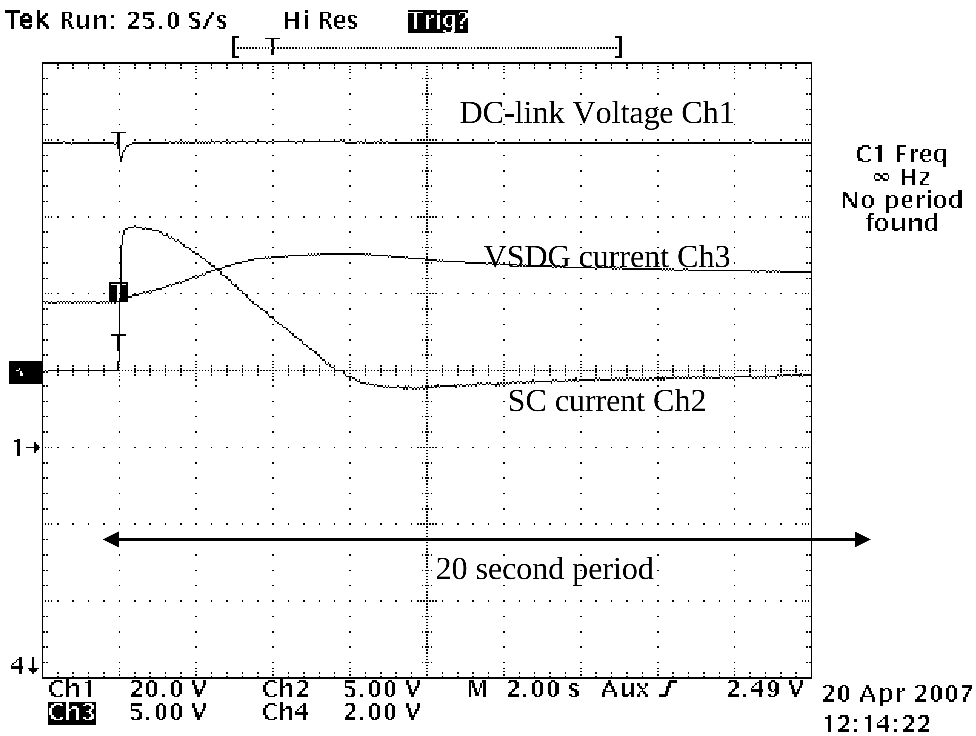


Figure 6.27 – VSDG with supercapacitor system step load response

The system is shown to respond as expected to the DC link voltage drop caused by the step load change. The moment the load increase is detected the supercapacitor immediately injects a large amount of current into the system helping restore the DC link voltage. While the supercapacitor is meeting the additional load, the VSDG accelerates to its new operating set point while gradually increasing its current loading.

The VSDG overruns its power set point slightly (under-damped control) allowing the Supercapacitors to regain some of the lost energy ready for the next load change.

The system was also tested for a reversal of the load step (load drop) previously applied and the response has been plotted below.

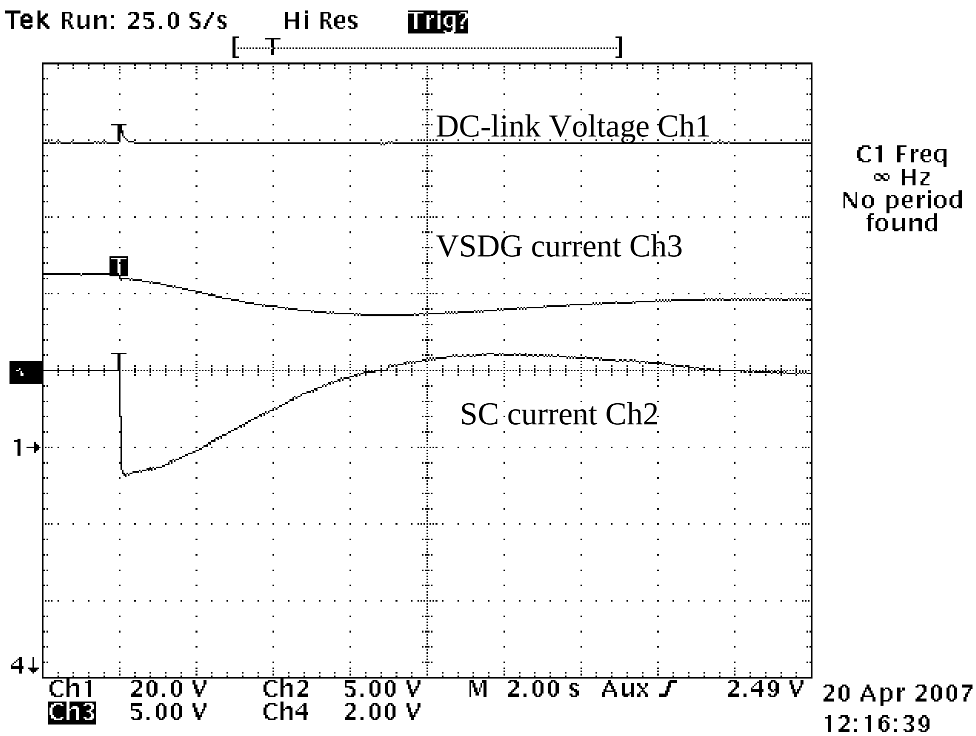


Figure 6.28 - VSDG with Supercapacitor system load drop response

The system was then tested for operation including PV to look for any instabilities or interactions that might occur between the different generators. The system initially had a load of 540 W with the VSDG supplying only 134W and the PV supplying the additional 450 W needed.

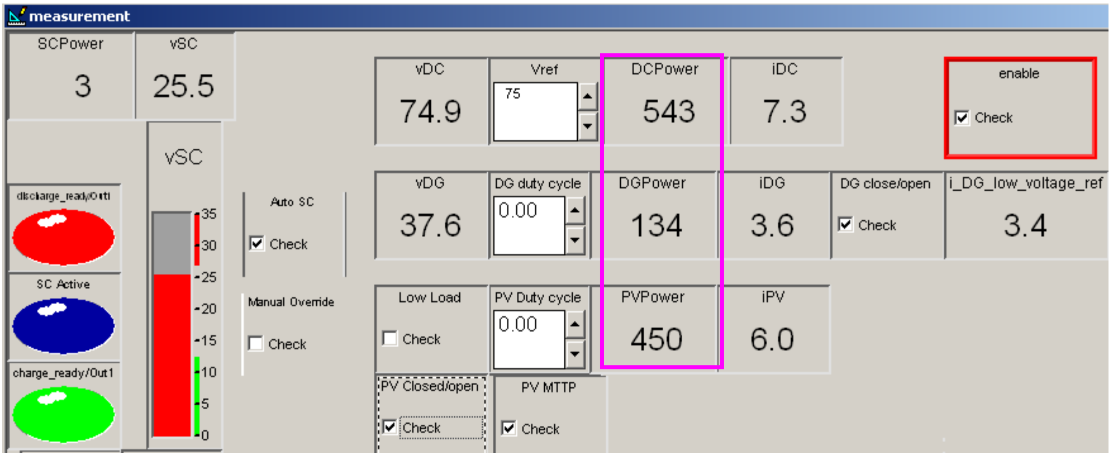


Figure 6.29 – ControlDesk Hybrid system setup before load step

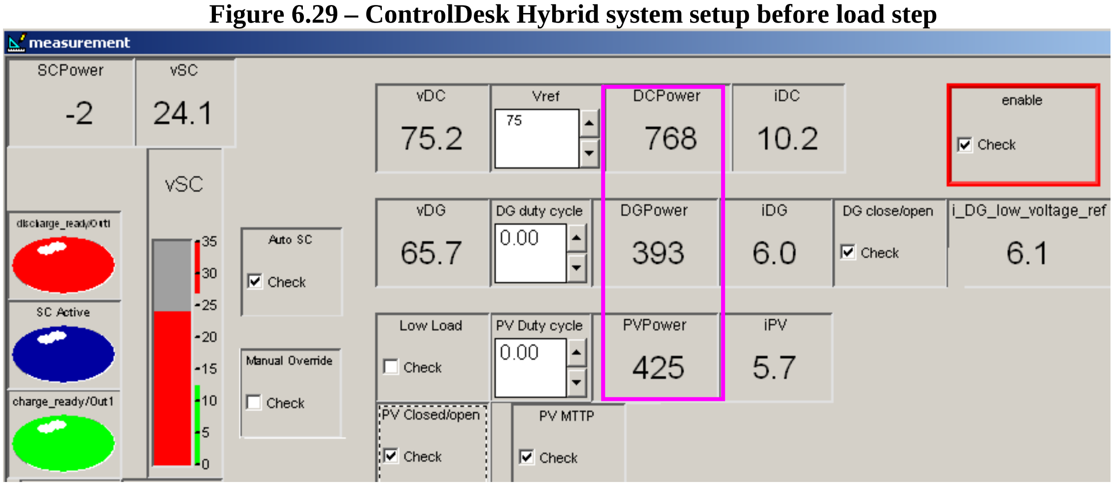


Figure 6.30 - ControlDesk Hybrid system setup after load step

The load was then stepped up to 768 watts with the PV power remaining approximately the same and the diesel increasing by the required amount. Below in figure 6.31 is a plot of the hybrid system response to the load step.

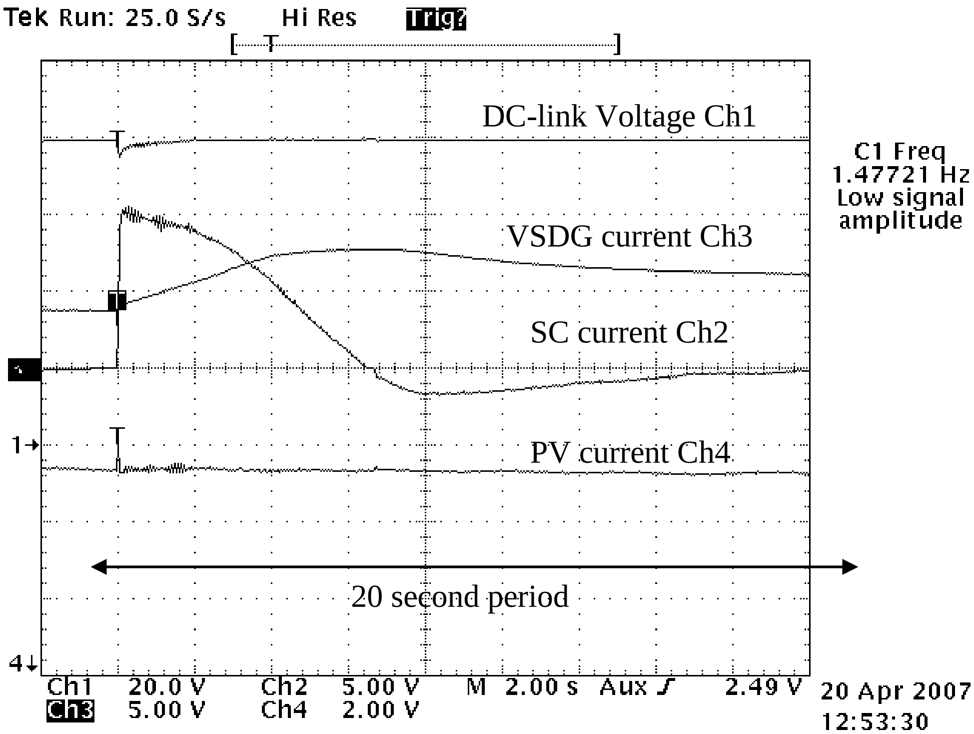


Figure 6.31 – Hybrid (VSDG-PV-SC) system load step response

As can be seen, the system reacts in the same way as before, and the PV power shows no drastic alterations. The experiment was then reversed, with the additional load being dropped. The hybrid system maintains DC-link stability and each of the components responded as expected.

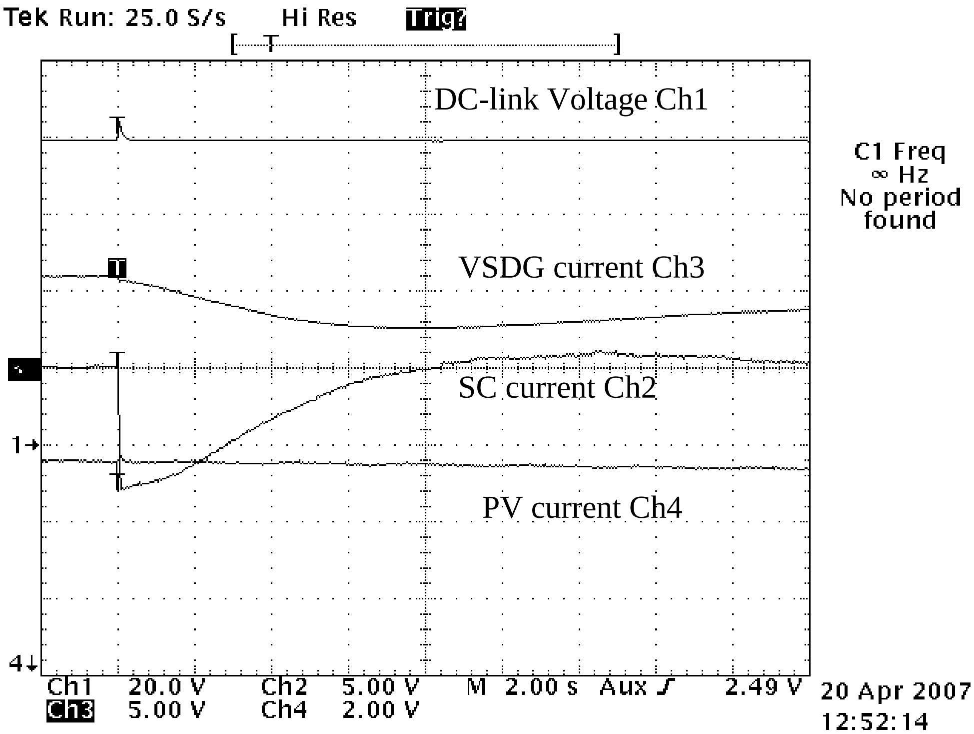


Figure 6.32 - Hybrid (VSDG-PV-SC) system load drop response

To assess the hybrid systems ability to provide stable operation under intermittent renewable generation, the solar readiation incident on the PV array was manually shaded, thus emulating cloud cover. The resistive load was kept constant throughout this test.

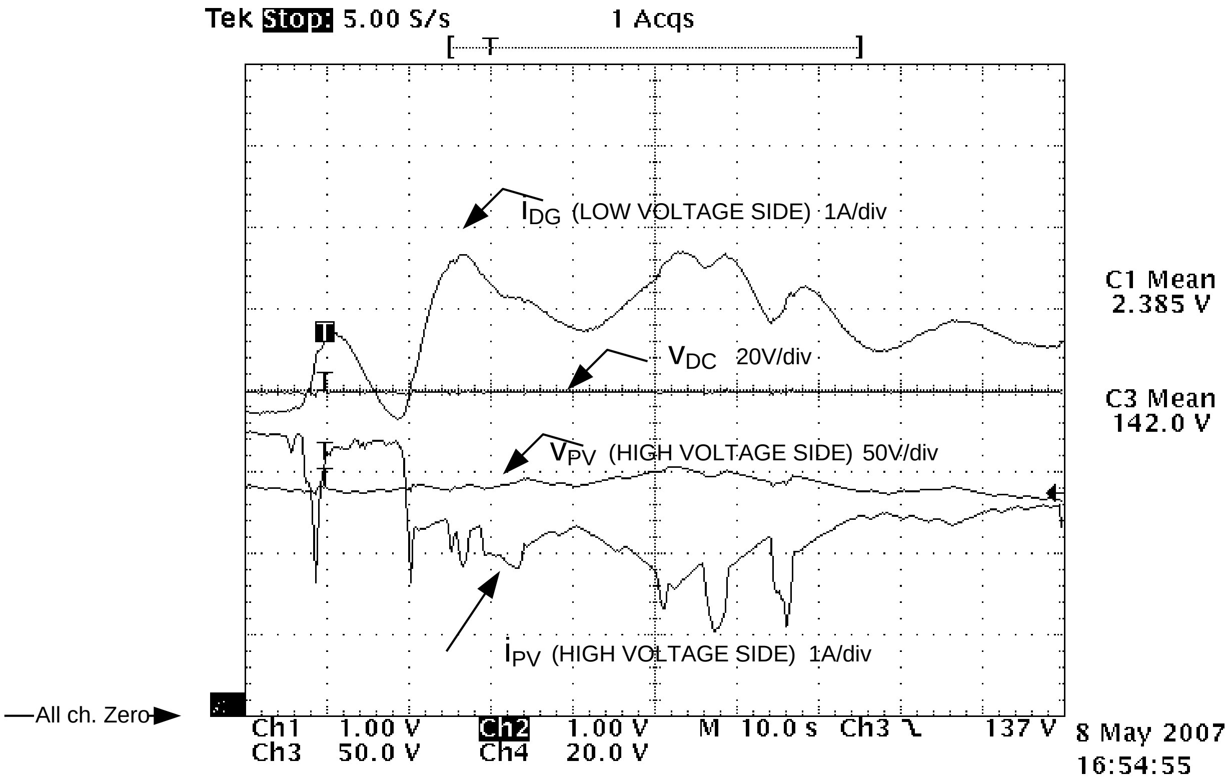


Figure 6.33 – Hybrid system response to PV shading

The Figure above shows the response of the VSDG current, DC-link voltage and PV voltage and current during this test. The VSDG current varies to meet the changes in load share, as the PV power fluctuates. Although not shown in the plot, the super capacitors are working to help maintain DC link voltage, which they can be seen to do effectively.

6.2 Testing at the University of Edinburgh

Initially, the power electronic and measurement equipment used in Italy had been transported to Edinburgh for use with the electrical machines and dSPACE available in the university power laboratory. After additional funding was attained, a set of power electronic and measurement equipment has been designed and built in Edinburgh, which will be presented in Chapter 7.

6.2.1 Components & testing arrangement

The layout of the full system used in Edinburgh and details of the power electronics are shown in Figure 6.34. A higher DC link voltage of 200V was chosen for this system due to the higher output voltage of the generators. All generation is primarily current controlled through PI controllers with the DC-link voltage being preserved through the controlled currents.

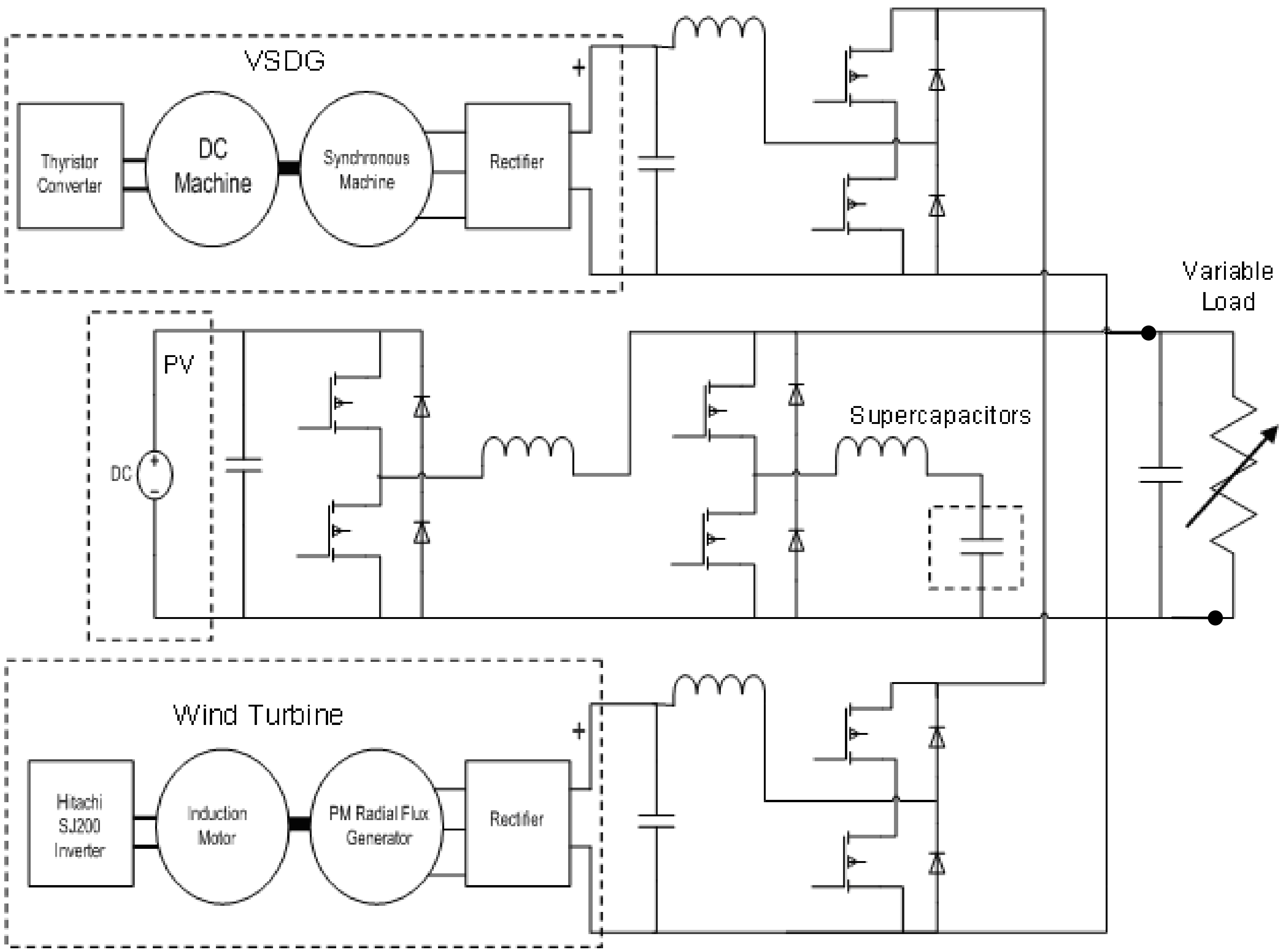


Figure 6.34– Edinburgh hybrid system layout

The VSDG has been emulated using a DC motor controlled by a thyristor converter to represent a diesel engine and an AC field wound Synchronous instead of permanent magnet generator. The simulated VSDG has to be controlled to work in unison with the Supercapacitors to maintain the DC-link voltage and hence system power balance. A MATLAB Simulink control system was developed for the hybrid system with particular attention required for the DC motor and AC generator control. In the previous test rig in Italy, the simulated diesel engine, then a SIMODRIVE PMM, was largely treated as a black box with a torque demand input. The input current to the DC motor has been controlled to achieve the required RPM through control of the thyristor gated AC/DC converter. As a diesel engine produces Torque as its primary output, the DC motor current input is converted to the torque equivalent using the relationship

$$T = K_T \times I \qquad \textbf{(6.4)}$$

K_T is calculated using the DC motors name plate power rating, RPM and current.

$$T = \frac{P}{\omega} = \frac{2601 watts}{78.66 rad/s} = 33.18 Nm \qquad \textbf{(6.5)}$$

$$K_T = \frac{T}{I} = \frac{33.18}{14.7} = 2.25 Nm/A \qquad \textbf{(6.6)}$$

The DC motor torque is limited in two ways; firstly, by using a cut-out switch when the current exceeds 12A and secondly, through the rpm torque limitation scheme for the chosen engine using a dynamic saturation block.

The AC synchronous generator has a current limitation of 6A placed on it to help avoid saturation.

The RPM speed reference has a linear relationship with the required VSDG power with a minimum set speed of 200 rpm and voltage error input. The actual RPM measurement is tapped from a laboratory rpm display box and reads the raw frequency pulse data.

The Supercapacitor system is current controlled under normal operating conditions using a PI controller with an absolute current cut-off loop. The single PI controller controls two IGBT switches, one for charging (step-down) and one for discharging (step-up). The sign of the Supercapacitor reference current determines which switch is allowed to operate. The Supercapacitor system disables charging above/discharging below set voltage levels.

The Supercapacitor control box directs the initial current demand change to the Supercapacitors and then slowly feeds the current demand to the AC generator through a purely integral control. In this way, the supercapacitors only supply power when absolutely needed during the initial transient.

The VSDG and supercapacitor system uses 4 current measurements, 3 voltage measurements and an RPM reading in the control and monitoring of the system. The current and voltage measurement positions in the hybrid system are illustrated below in Figure 6.35. There are 7 nested PI control loops, although not all of them work at the same time. The base control for all the system variables is the DC-link voltage error measurement.

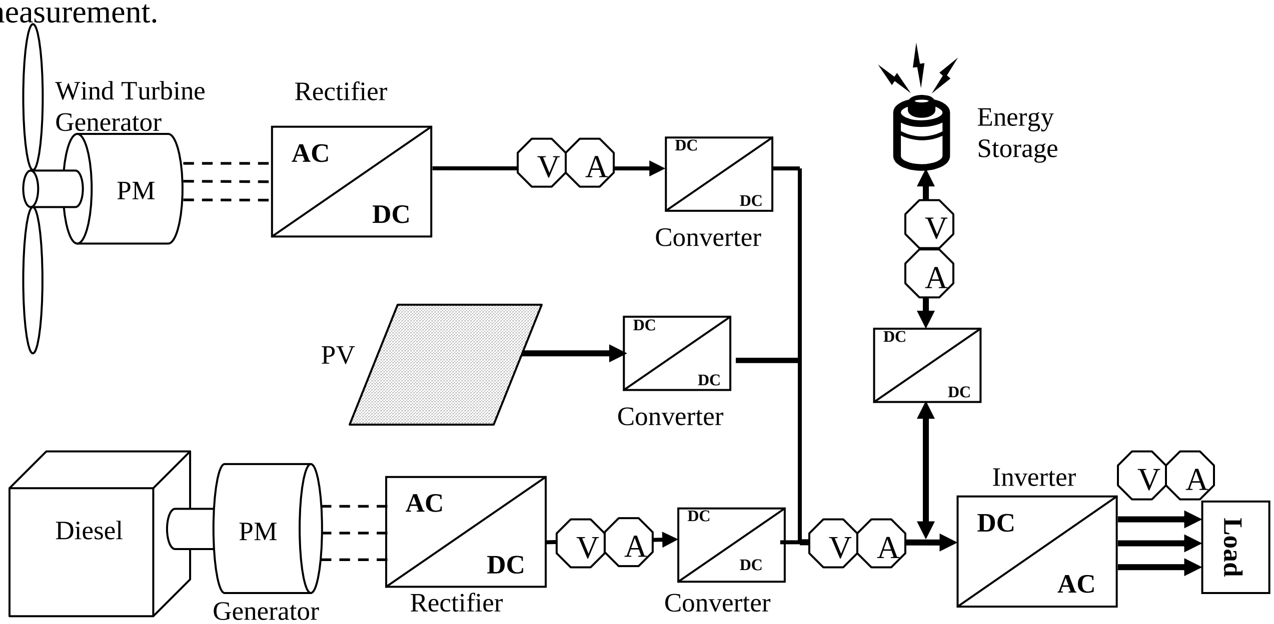


Figure 6.35 – Voltage and current measurement positions

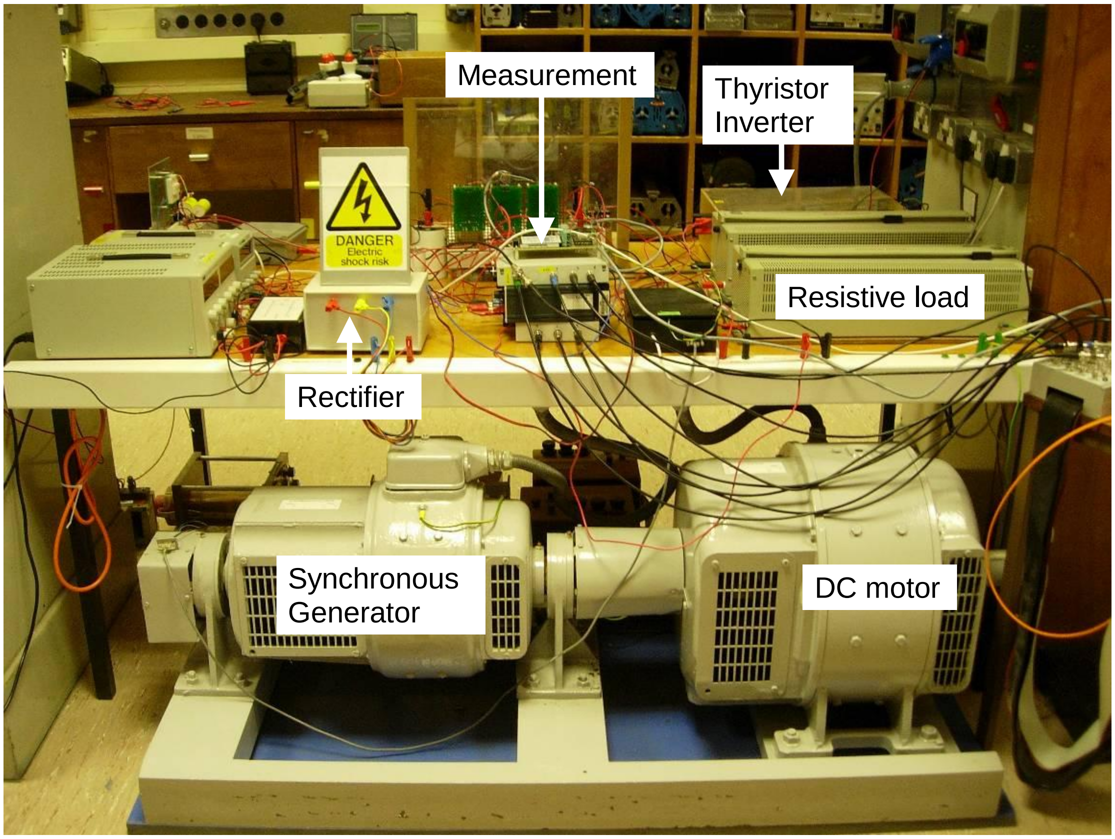


Figure 6.36 – Experimental Setup picture

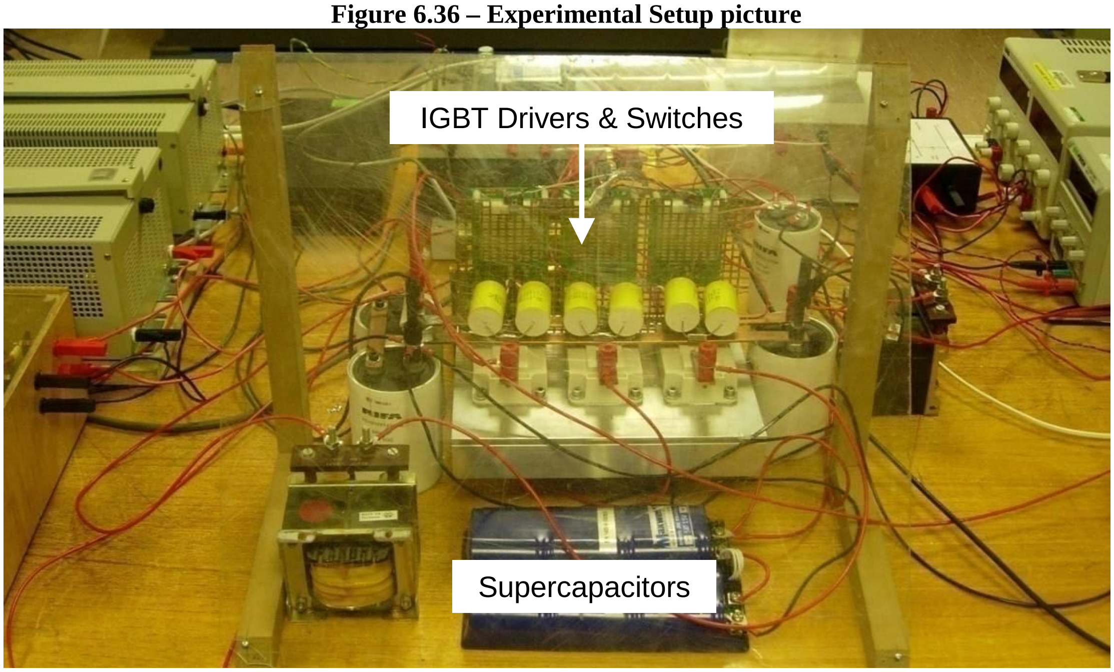


Figure 6.37 - Switches and Supercapacitors picture

The supercapacitor system includes up to five 15V 58F Maxwell Supercapacitor module in series (75V 11.6F), although it was found to run adequately on only three.

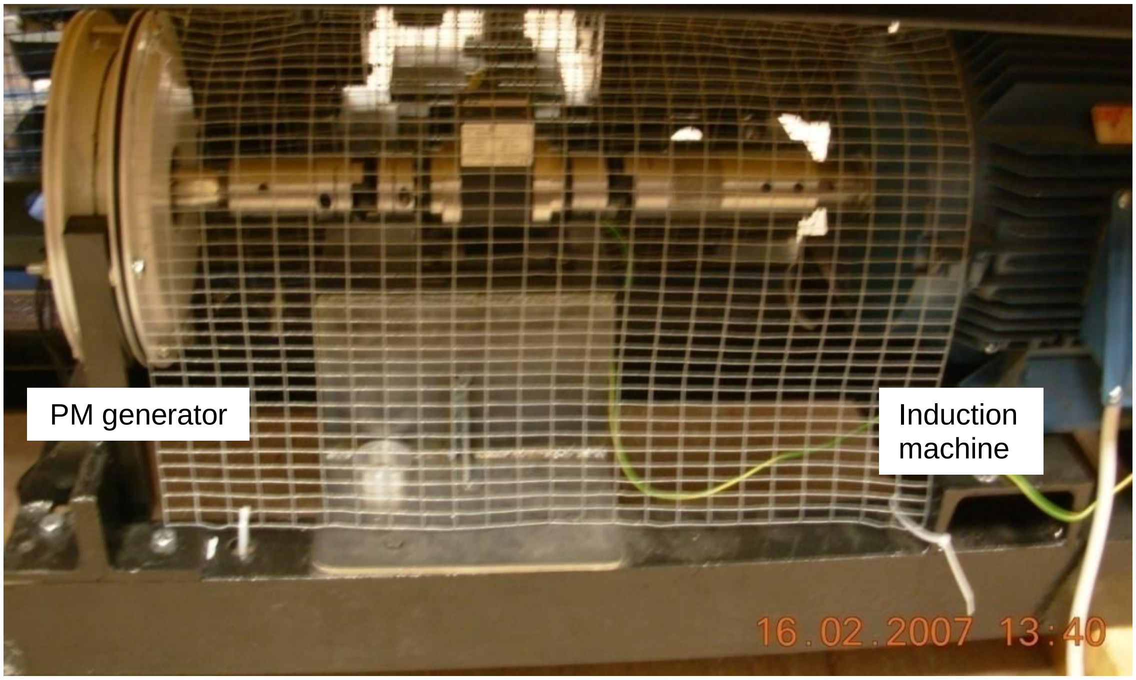


Figure 6.38 – Wind Turbine Simulator setup picture

The wind turbine rotor-wind speed interface is simulated through an inverter (7.5kW IGBT) driven induction motor mechanically connected to the PM generator (Swift 1.5kW wind turbine). The effective wind input is changed by means of frequency control of the inverter. The output of the PM generator is then rectified to DC and boosted up to the DC link voltage.

The PV has been replicated through a fixed voltage DC source and variable resistor. Due to a lack of a proper PV simulator (or time and resources to make one) the MPPT has not been implemented in Edinburgh due to the different operating method of the power source. The power source is manually varied through the variable resistor, which changes the share of the power supplied. The power source can therefore be controlled to act like PV as an uncontrolled generation source, which is needed in the assessment of the hybrid systems stability (VSDG-SC).

6.2.2 Experimental Test & Results

To assess the performance of the hybrid system, it was subjected to a number of tests both with and without the addition of the supercapacitor energy system.

In Test 1, the power was divided as follows: DC load 580W, VSDG power 270W, PV power 80W and Wind Turbine power 230W. The large proportion of wind power is then dropped adding an extra 230W of load to the VSDG. Figure 6.39 illustrates the potential improvement of the hybrid system DC link stability with the supercapacitor energy system. The dc link voltage drop without supercapacitors is much deeper and more prolonged than with the Supercapacitors and therefore far more pronounced and potentially detrimental to power quality/grid stability.

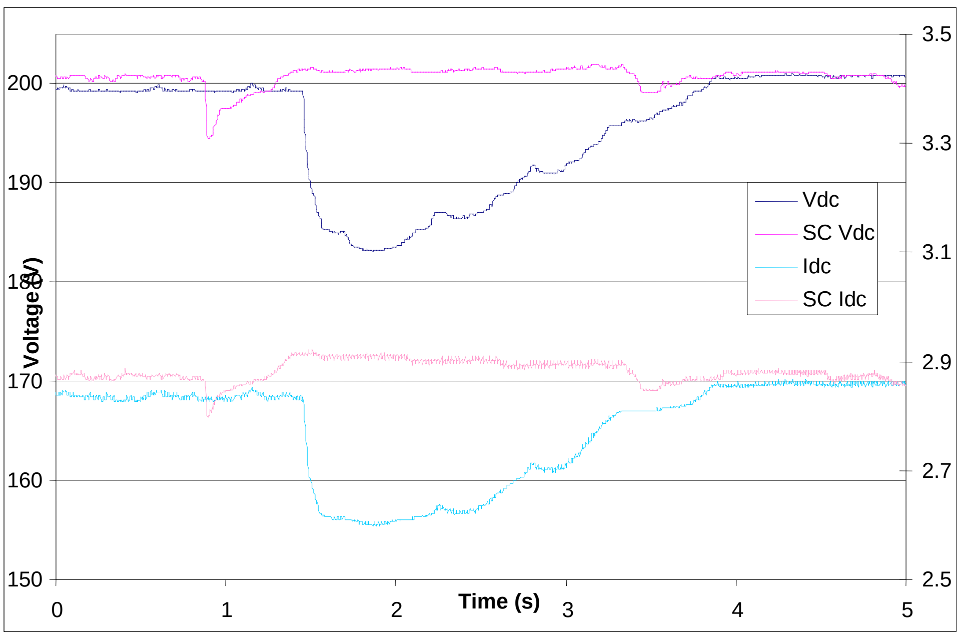


Figure 6.39 - DC link stability for wind drop

(Measurements with the prefix SC are results for the system with supercapacitors)

The shortfall in power from the hybrid system without the Supercapacitors causes the voltage to drop to 182V and it takes over 2 seconds for the voltage to recover. If the system was connected to a three-phase load through an inverter, the voltage drop (power deficit) could be even greater if the inverter maintains a constant power regardless of DC-link voltage.

In Figure 6.40 the balance of power from the VSDG and the Supercapacitors during the wind power drop can be examined.

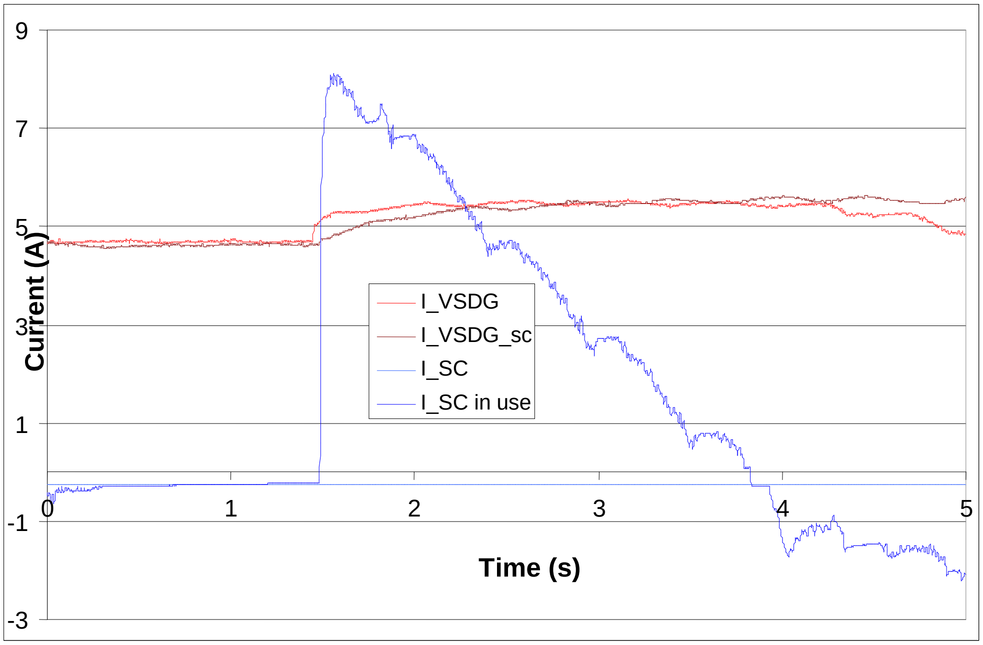


Figure 6.40 - VSDG and SC response to wind drop

The difference between the two schemes is clear, to see with the supercapacitor current (and hence power) shooting up in accordance with the control scheme described earlier to instantly meet the new power balance. The delay in current take up by the VSDG with the supercapacitor system is also noticeable and confirms the system is operating as expected.

Fig 6.41 looks at the wind power drop during the test, as the current falls sharply from 4 to 0.6A and then continues to decrease more slowly.

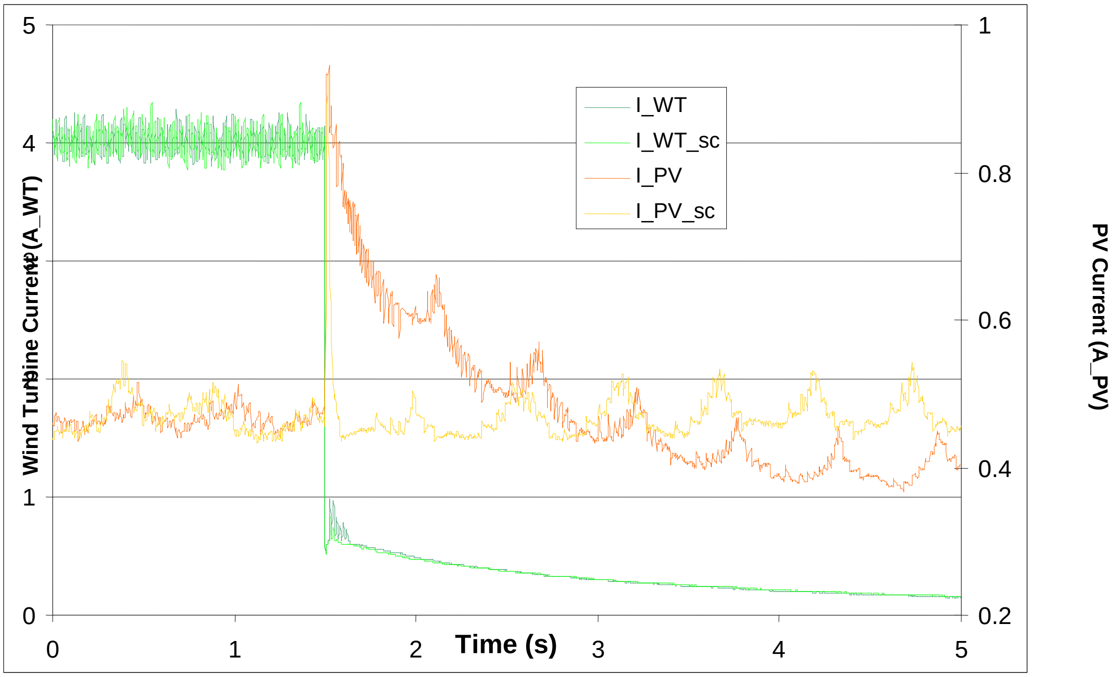


Figure 6.41 - Wind turbine and PV outputs during wind drop

There is also a momentary increase in the measured PV current during transition that can be attributed to the reduction in DC link voltage causing the power drawn from the emulated PV to increase.

Test 2 involved a step load being applied while the PV and wind power remained constant. The division of power for this test is as follows: DC load 330W, VSDG power 220W, PV power 60W and Wind Turbine power 60W. The DC load was then stepped up to 540W and the resulting DC link response is shown in Fig 6.42. Again, the superiority of the hybrid system with the Supercapacitors is clear with only a negligible voltage drop. The response of DC-link current differs from that observed in Figure 6.39, as an increase in current is needed. It can be seen that the hybrid system without the supercapacitor energy storage initially reacts well meeting the new operating current. This can be attributed to the extra available VSDG current and stored power taken from the DC link capacitors.

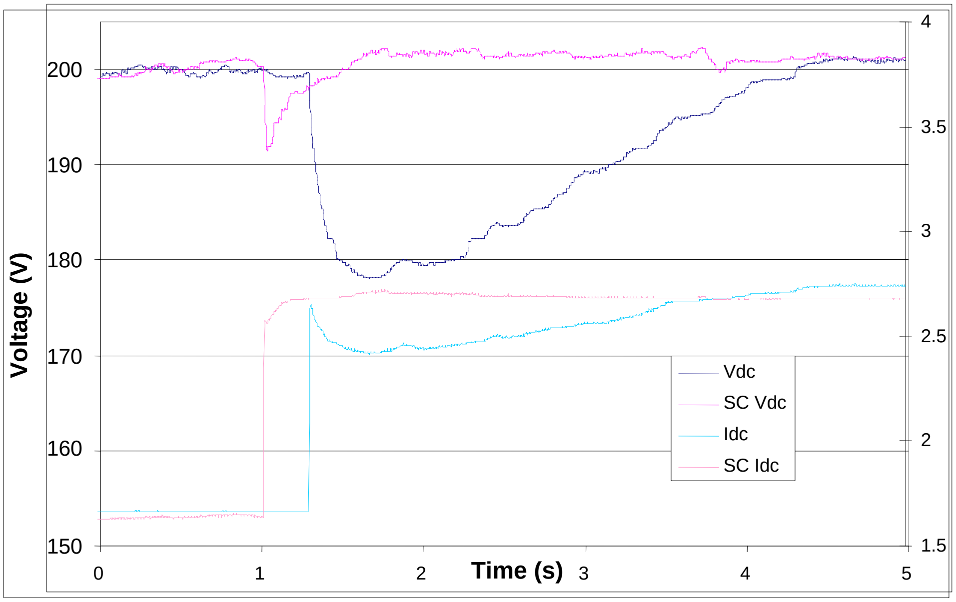


Figure 6.42 - DC link stability for load step

Once the VSDG current reaches the current limit (used to help prevent engine stall and generator saturation) the system is in the situation where the diesel engine needs to accelerate to the new power set point, but because the engine is highly loaded, it struggles to do this and therefore the DC link voltage and current drops. Figure 6.43 shows a similar operation of the VSDG and supercapacitor to the wind drop test and demonstrates that the system is operating as expected.

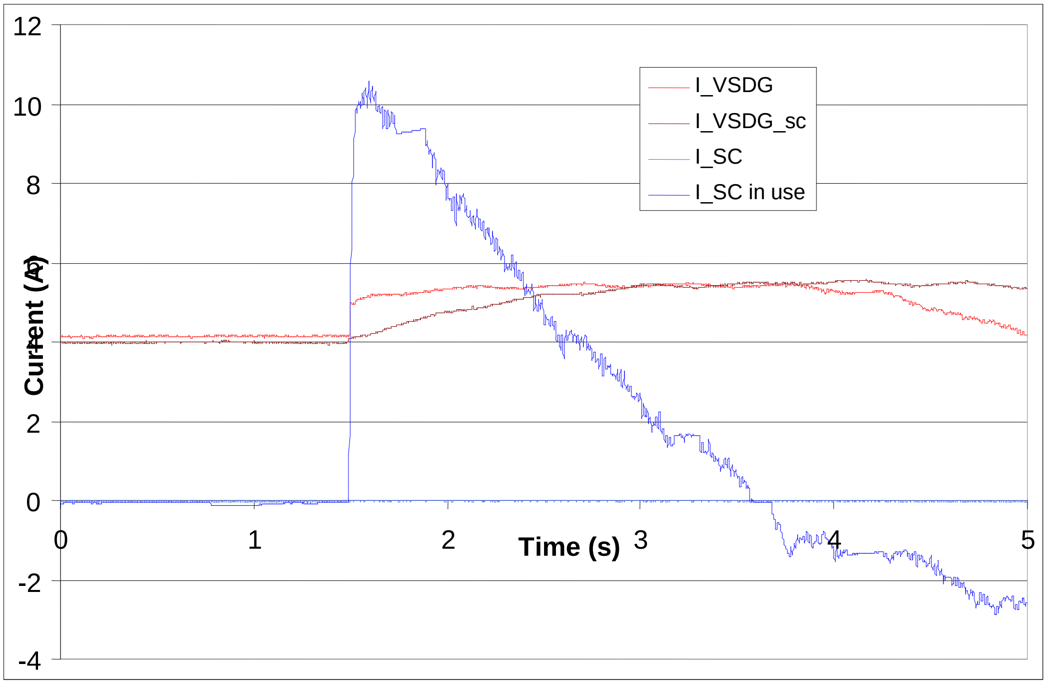


Figure 6.43 -VSDG and SC response to load step

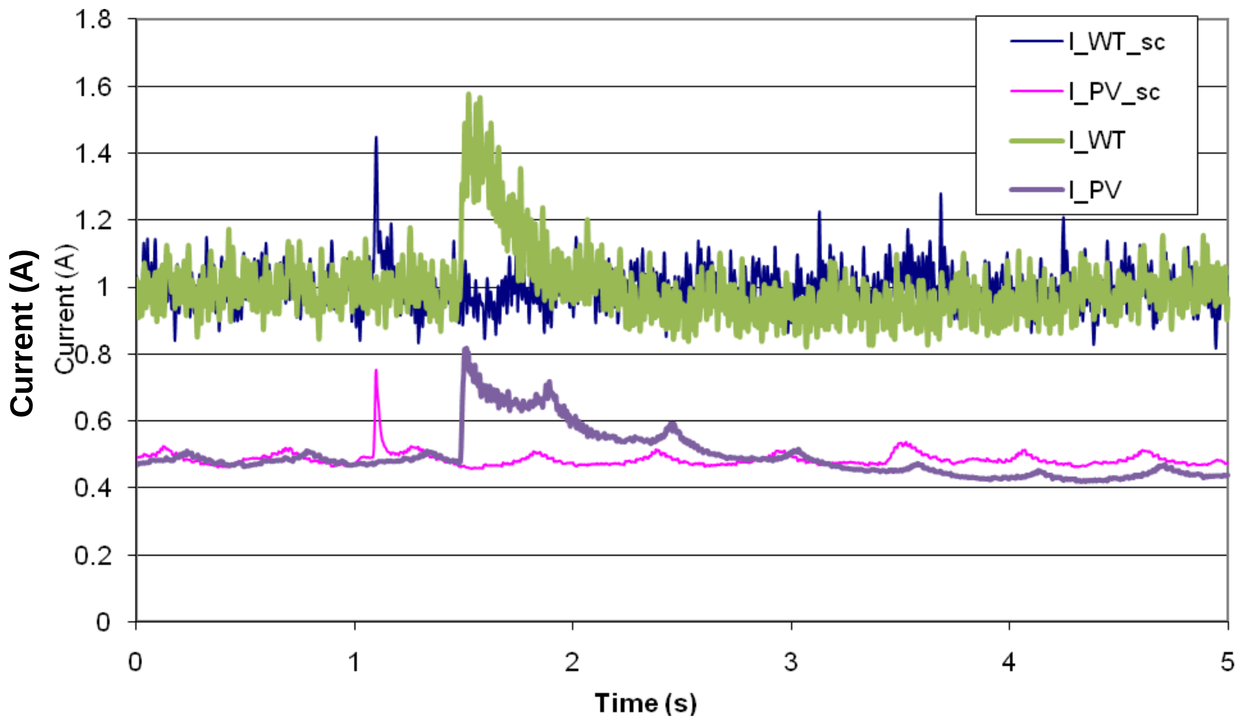


Figure 6.44 - Wind turbine and PV outputs during load step

Figure 6.44 again illustrates that the PV and wind turbine currents increase with the DC link voltage drop, but the rest of the time their power remains steady and system stability is not affected.

Test 3 DC – AC power conversion

Due to extra funding for some additional work on the variable speed hybrid system concept an inverter and extra measurement devices have been built. The inverter has been loaded by three individual star connected resistive loads and power has been supplied to the inverter by the emulated VSDG.

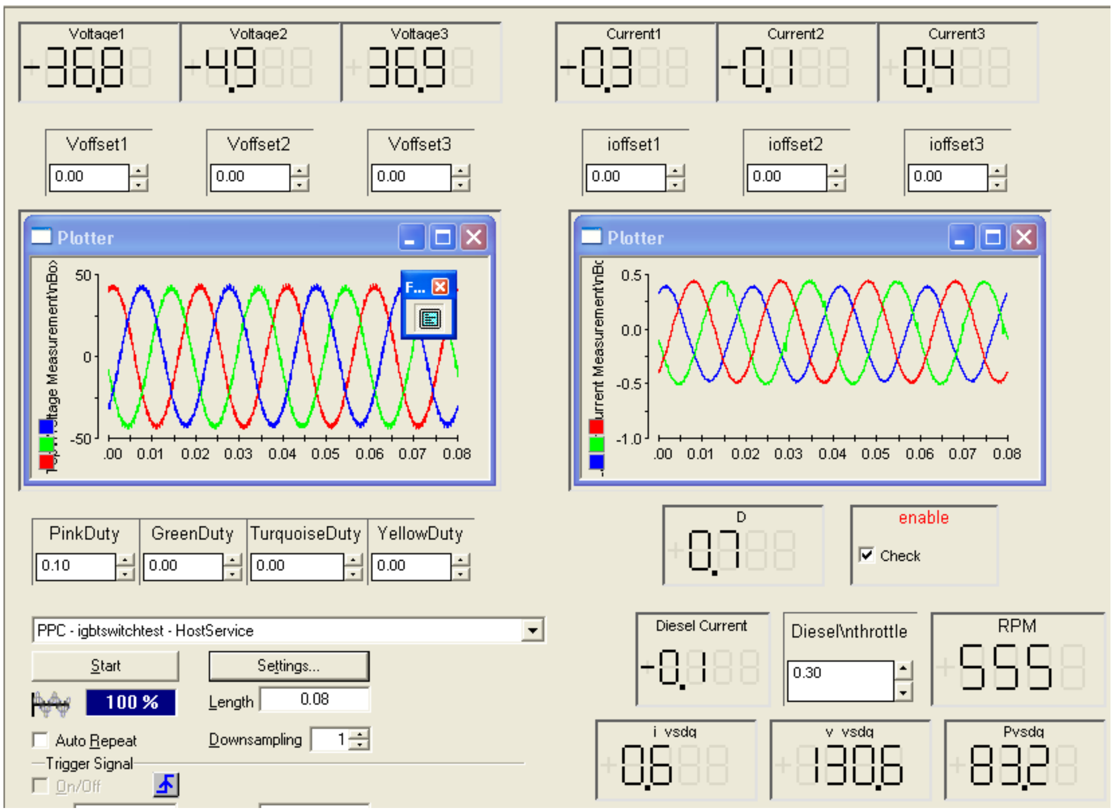


Figure 6.45 -dSPACE ControlDesk VSDG fed inverter

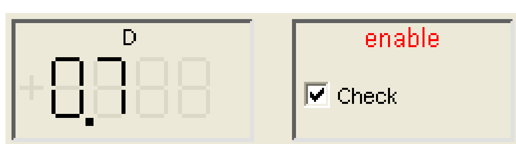


Figure 6.46 -Automatic inverter control (Duty cycle to maintain constant voltage output)

A sine wave generator creates the base signal for the individual phase dSPACE PWM input. This is then modified to achieve the required voltage output level by increasing or decreasing the gain (D - Duty modulation in Figure 6.46) of the sine wave. The difference between the average RMS voltage measurement of the three phases and the reference RMS voltage is used as the error input to the sine wave gain control (Duty Figure 6.46). An overview of the inverter control in simulink is shown below in Figure 6.47.

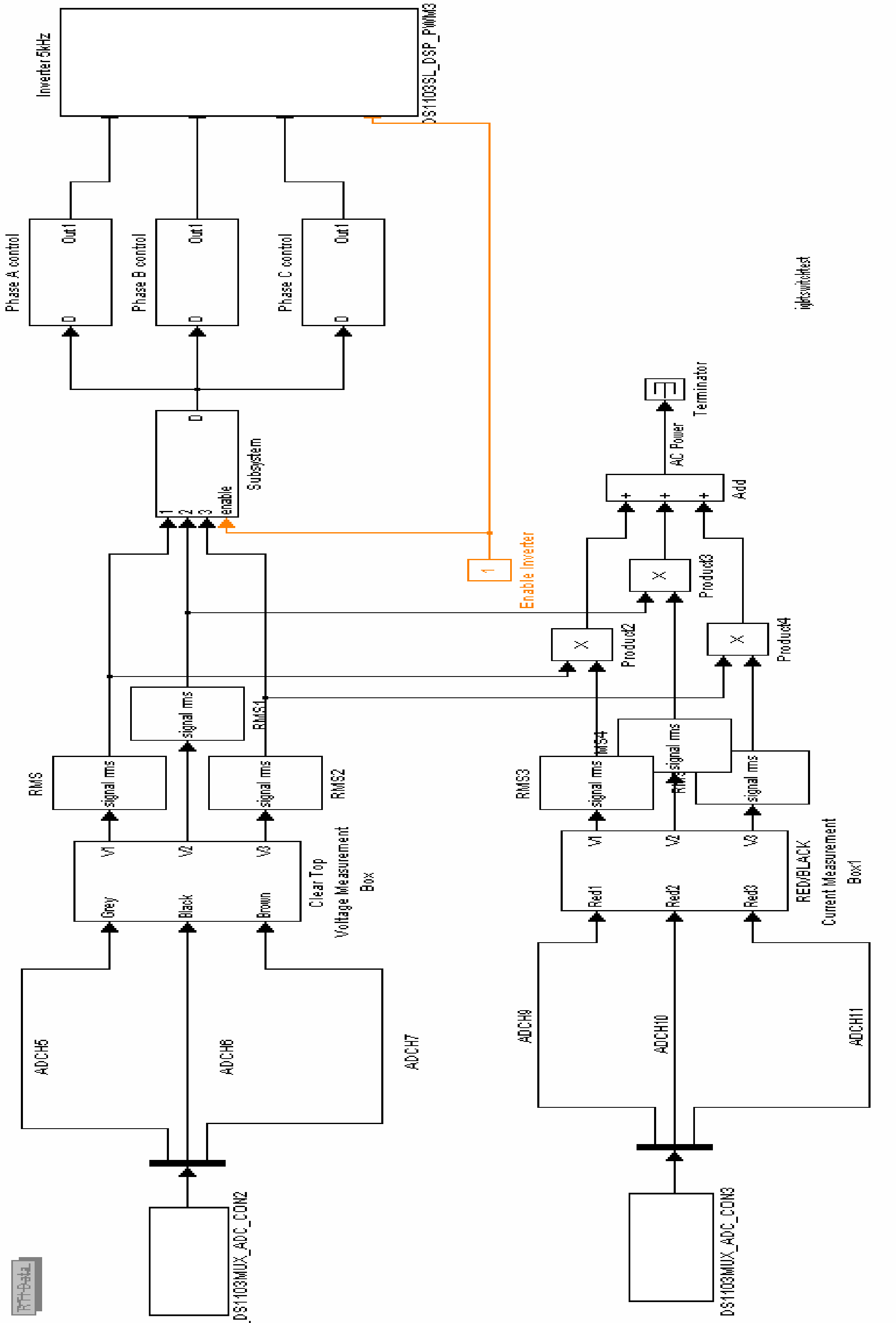


Figure 6.47 – Simulink inverter control model

Below are the 3-phase voltage and current outputs from the inverter during steady state testing.

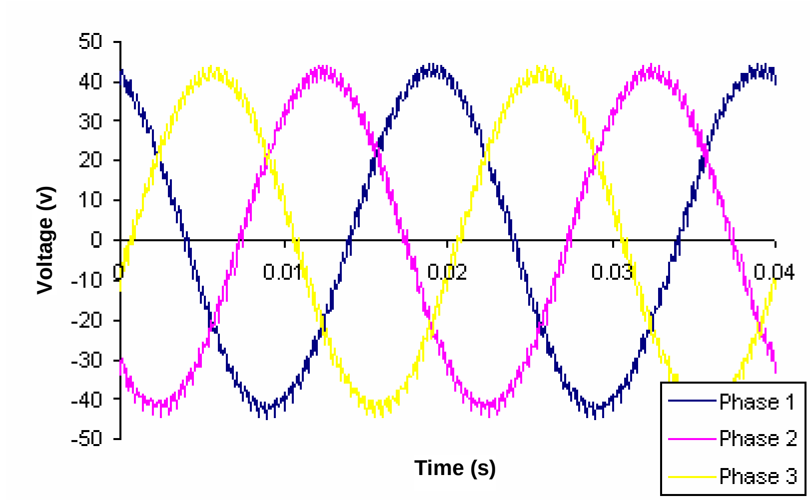


Figure 6.48 – 3 phase voltage output

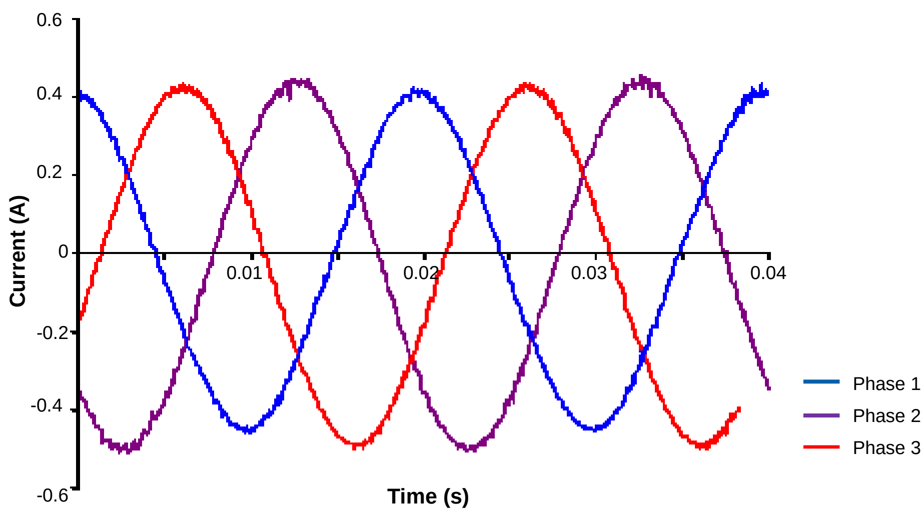


Figure 6.49 – 3 phase current output

Even at these low voltage and power settings, the harmonics in the outputs are quite small (4%-5%). The filtering of the inverter output has been carried out using the available inductors and capacitors in the Edinburgh University power laboratory. Below is the complete Matlab Simulink model for the VSDG driven inverter.

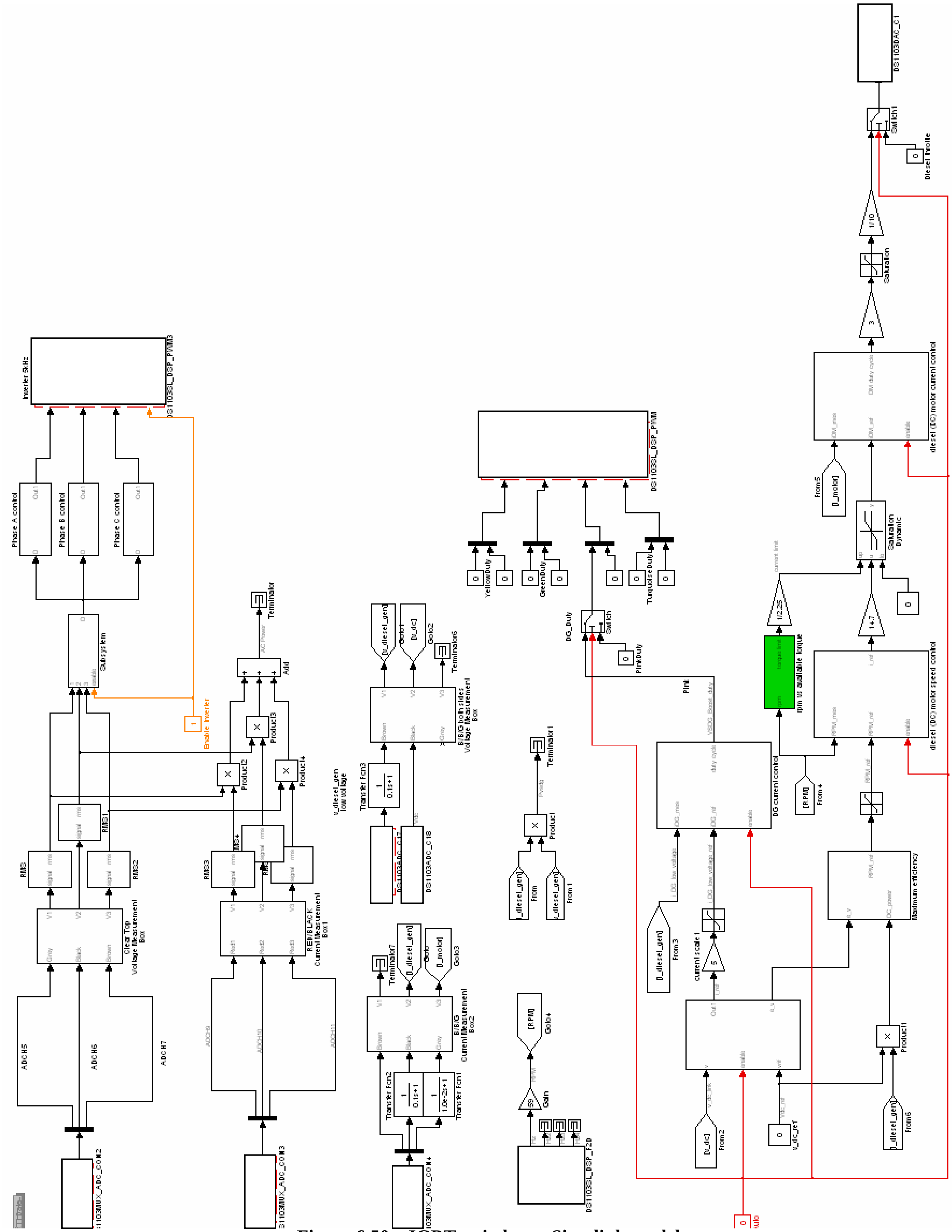


Figure 6.50 – IGBT switch test Simulink model

6.3 Summary

This chapter has looked at the low power experimentation performed at the University of Cassino, Italy and the University of Edinburgh, UK. Experiments have been carried out in order to verify the control strategies and models previously created and tested in Matlab Simulink.

The different experimental setups are described and the equipment used is specified and schematics of the system layout have been detailed. The performance of the system is assessed and some of the problems encountered and their solutions are discussed.

Fine-tuning of the control strategies has been carried out to provide better control and overcome practical problems encountered. The PV Maximum Power Point Tracking (MPPT) control has been detailed and the operation demonstrated and shown to work satisfactorily.

The need for the addition of a power boost component to help stabilise the hybrid power system during heavy load transients and renewable power fluctuations has been shown. The improved stability of the VSDG with the Supercapacitor power boost system has been demonstrated both under load steps and with renewable power fluctuations.

A three-phase inverter has also been constructed and tested using the emulated VSDG as the power source.

7 High Power Experimentation

Due to the donation of a Variable Speed Integrated Genset (VSIG) from Cummins Generator Technologies and the availability of prototype direct drive 20kW permanent magnet (PM) generator and test rig at the University of Edinburgh, high power experimentation has been carried out.

7.1 Components & Setup

The high power hybrid test rig layout is show below in Figure 7.1. The main components are the 15kW VSIG, 20kW PM generator, supercapacitor load levelling, inverter and DC/DC converters.

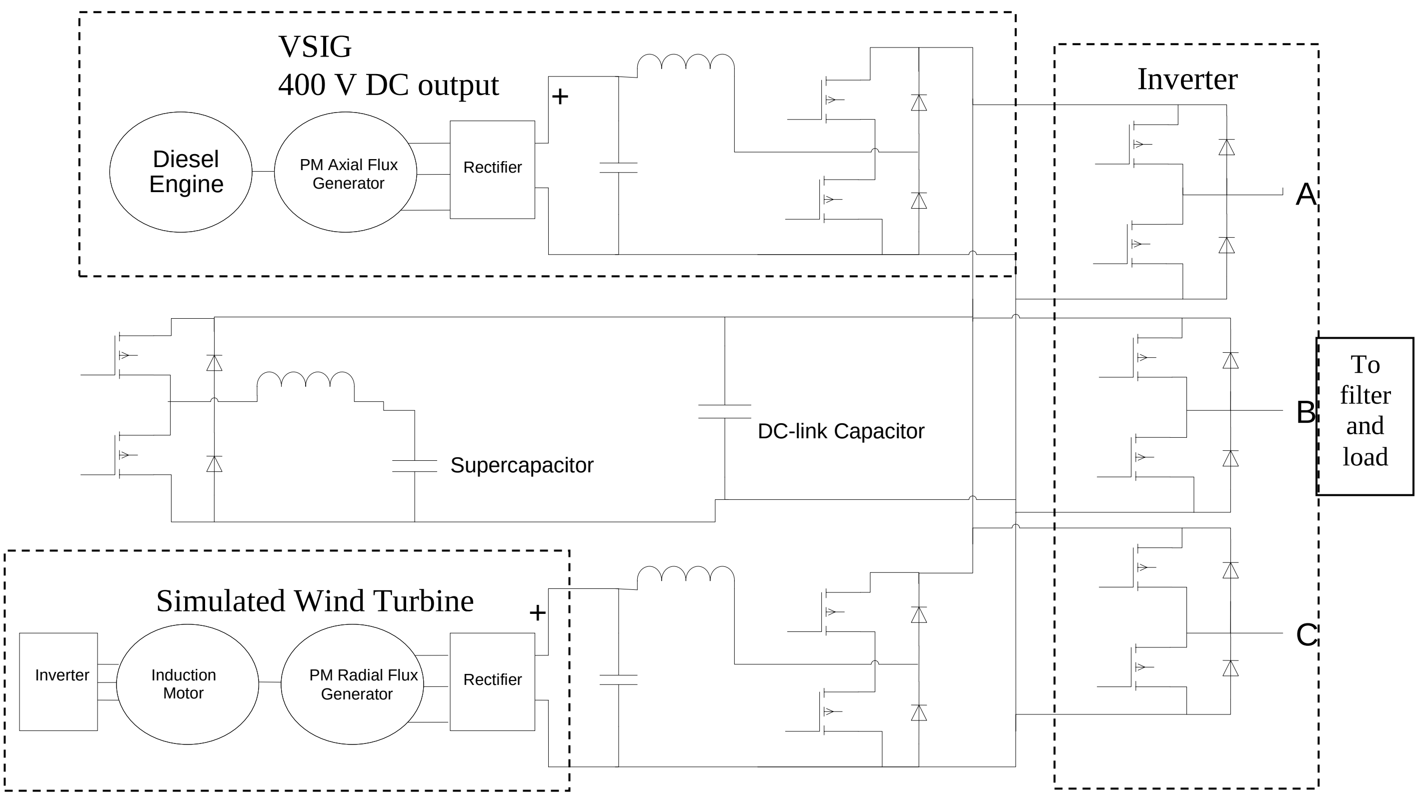


Figure 7.1 - High Power Hybrid Test rig Layout

The wind turbine, Supercapacitors, inverter and DC/DC converters are all controlled through dSPACE. The VSIG, Figure 7.2, has its own control module that tries to maintain a constant 400 volts DC output which is connected directly to the DC-link.

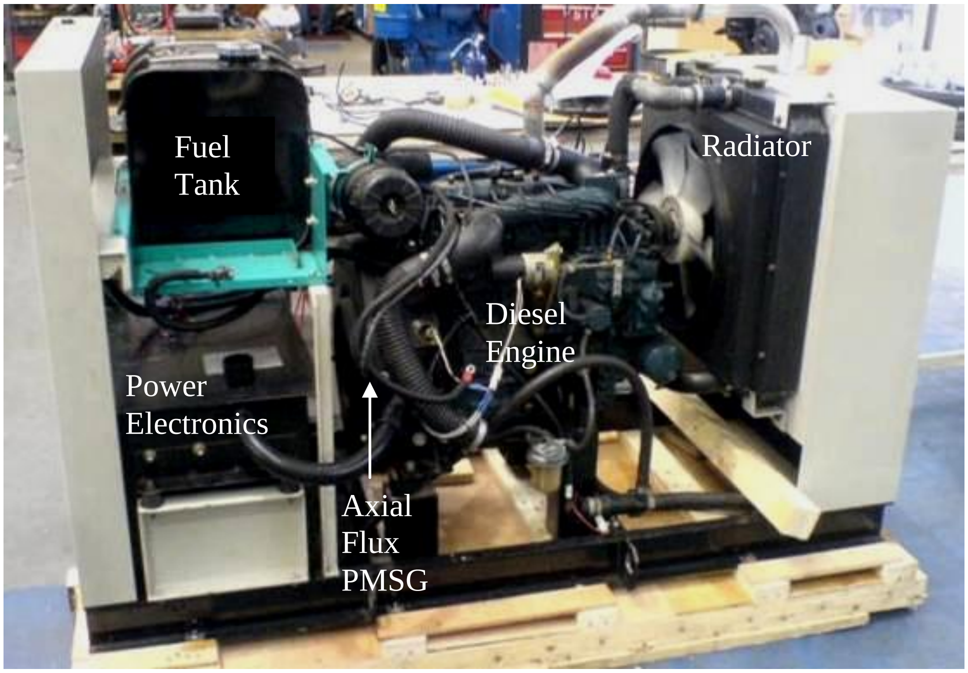


Figure 7.2– Variable Speed Integrated Genset (VSIG)

The low speed direct drive PM wind turbine generator is driven through a gearbox by an inverter controlled induction machine, Figure 7.3. A wind speed input is converted in Simulink through a wind turbine rotor model. The generator's equations of motion and the wind turbine control are used to produce the modelled generator rotational speed. This speed signal is sent from the dSPACE board to the inverter, which produces a variable frequency to power the induction motor at the correct speed for the wind input. The induction motor is connected to the 20kW PM generator via a step down gearbox. Power is then taken from the wind turbine generator and rectified in the connections box shown in Figure 7.3, before being connected to the power electronic box in the Figure 7.4. Here the voltage will be stepped up to that of the DC-link, 400V. The connection box also supplies DC voltage and current readings which are connected to the dSPACE board.

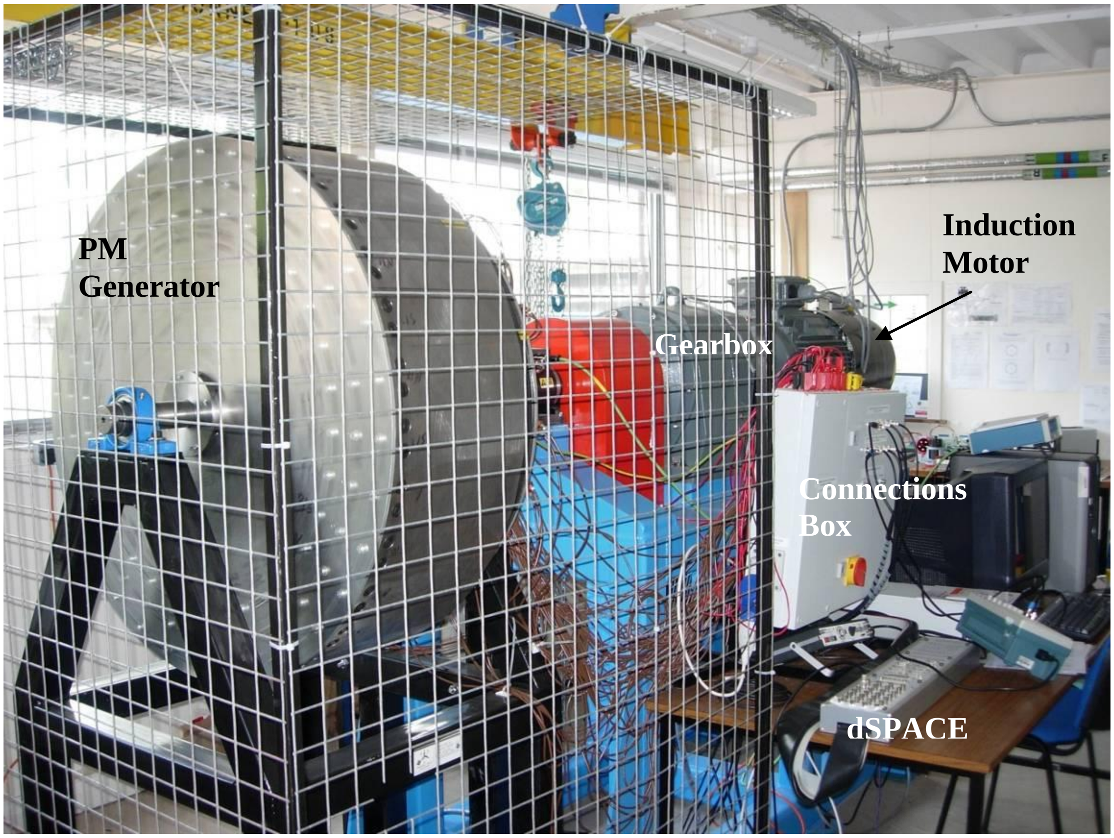


Figure 7.3 – PM wind turbine generator test rig

As well as receiving and converting power from the wind turbine simulator, the power electronic box in Figure 7.4 also houses the supercapacitors. The supercapacitors are connected to the DC-link through a step up/down converter. Also contained within the box are three current transducers, the signal processing circuits and their power supply.

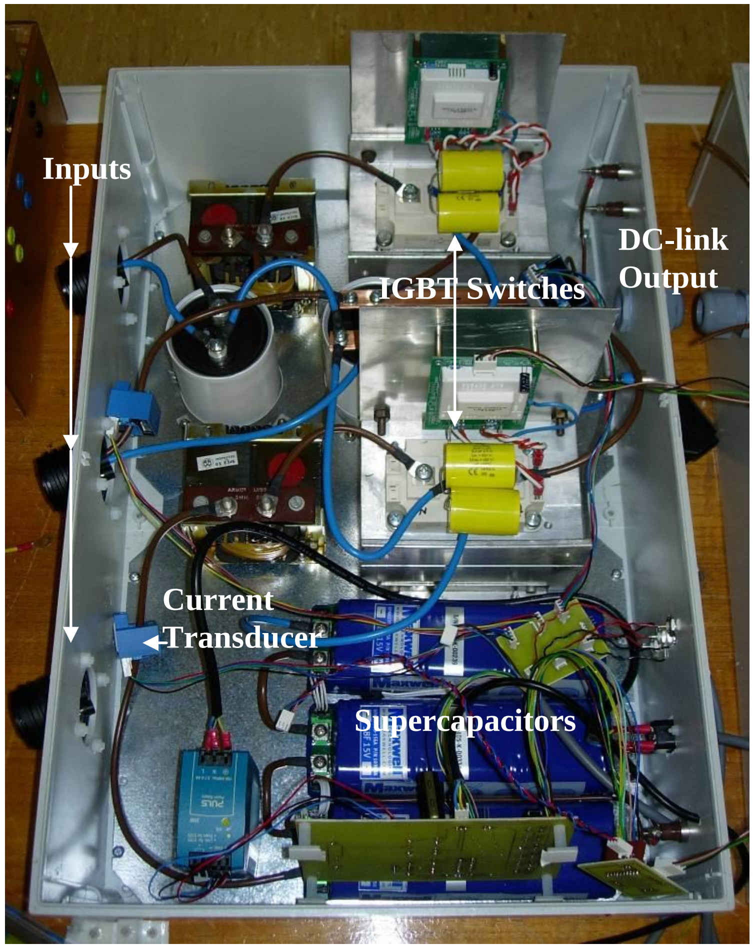


Figure 7.4 – Supercapacitors and DC/DC power electronic converter box

The inverter box in Figure 7.5 has a direct connection to the power electronic box (Fig 7.4) through the DC-link. This feeds the inverter IGBT switches, three dual-IGBT modules, which convert the DC power into AC. The raw AC power is then filtered through a basic capacitor and inductor arrangement before being passed to the AC output connector. The box also contains three current transducers and their signal processing circuit board.

The AC output is then connected to a 3-phase resistive load bank, which allows step changes in the load to be applied.

The voltage measurement is taken care of by the same measurement boxes used in the low power experimentation.

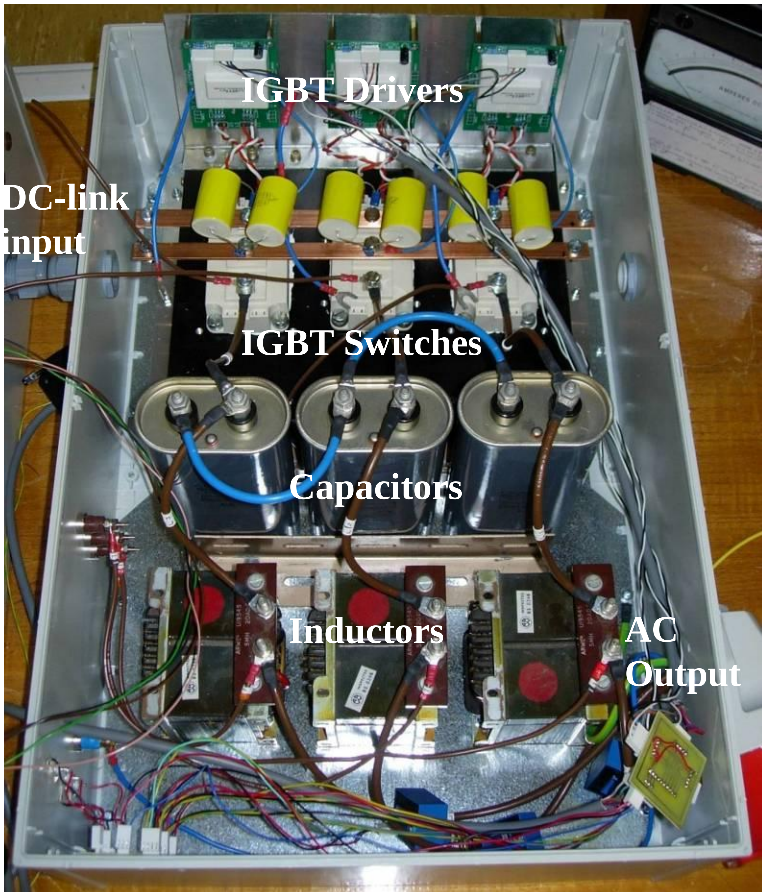


Figure 7.5 – Inverter power electronic box

7.2 Experimental Test & Results

Due to the limited time available and delays in the test rig setup, only some initial test runs have been carried out. These involved running the wind turbine up to speed and connecting the VSIG up to the power electronic boxes.

The wind turbine power was fed through the power electronic boxes to the three phase load for a number of different loads. The graph in Figure 7.6 below is taken from the oscilloscope capture of the wind turbine supplying a 2kW load. The readings of all 3 voltages and a single current measurement have been taken. It can be seen that the voltages are balanced and the harmonic content is low (3%-4%) even at the low power levels in this test.

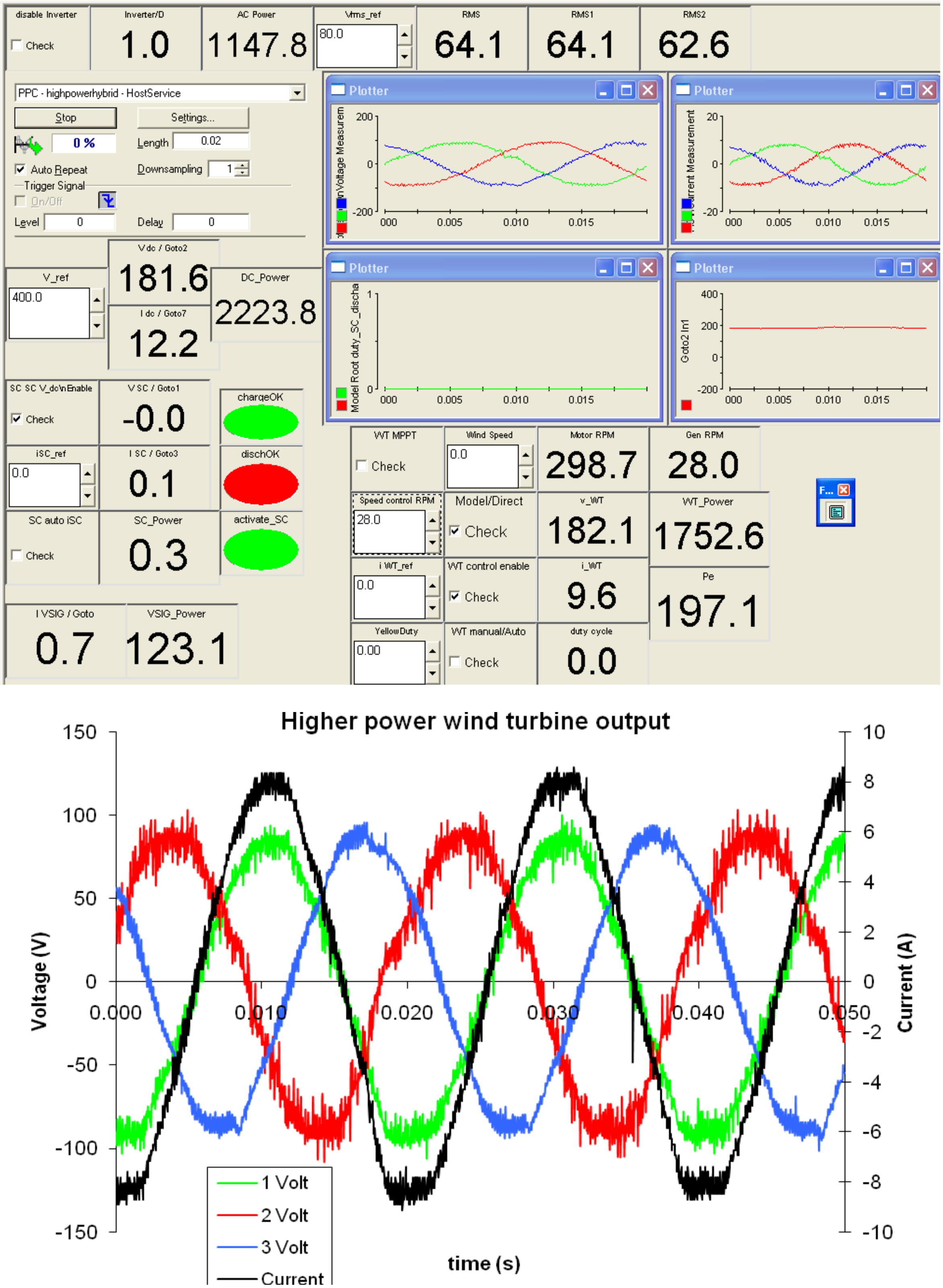


Figure 7.6– 2 kW wind turbine

The speed of the wind turbine generator was then increased, but one of the IGBT driver modules would cut out at higher voltages and produced a short circuit error even though this should not be possible with the control signal input and gate driver control.

The VSIG has yet to be fully tested, as this gives a constant 400 Volt output which causes the inverter to operate incorrectly due to the error signal problem.

7.3 Summary

The high power test rig has been setup and some brief initial functionality tests carried out. This demonstrated that at low voltage levels the inverter operated correctly but problems occurred at high voltages. It is expected that some elements of the IGBT gate driver may need to be changed in order to facilitate the correct operation of the inverter.

It is also expected that an increase in the number of supercapacitors would be beneficial to the stability of the hybrid system operation.

Further tests to be carried out include:

- Steady-state load test of the complete hybrid system.
- Constant load under varying wind speeds.
- A varying load test with constant wind power input
- Assess the hybrid systems ability to maintain power quality under load or wind speed changes.

8 Conclusion & Future Work

This thesis looks into the possibility of reducing the cost of electricity for off grid communities that currently rely on diesel gensets by integrating a VSDG into a renewable hybrid power system. A brief summary of each chapter in the thesis and the important conclusions are included in this chapter.

8.1 Discussion

Each chapter in this thesis has been provided to support the use of variable speed diesel generators in an integrated hybrid system to help reduce fuel use and the overall cost of electricity.

Chapter 2 establishes the history of and uses for diesel generators and explains the problems with conventional constant speed diesel generators of low part-load efficiency and minimum loading. It than goes on to explain how variable speed operation of the diesel generator overcomes these problems and the possibilities this brings in terms of fuel savings. Some potential disadvantages of variable speed operation compared to constant speed are also discussed.

In Chapter 3, the idea of hybrid power systems containing renewable generation is introduced and examples of current systems in operation are reviewed. The different generation and energy storage options currently available are discussed and a case study of the hybrid power system on Foula, a small Scottish Island, is detailed.

The initial feasibility of the variable speed diesel generator both as a standalone unit and as part of a hybrid power system supplying a small community have been modelled in Chapter 4. Substantial fuel savings have been calculated allowing confidence in the continuation of the research due to the potential of the idea to provide cheap electricity to the chosen communities. After more research and simulation had been undertaken, a better understanding of the costs, operation and components necessary for the proposed variable speed hybrid system has been gained. This allowed a more comprehensive lifetime economic feasibility model of the system to be simulated, which showed a significant reduction in the cost of electricity for the chosen community. It also showed a reduction in the cost of electricity over many sensitivity combinations, with only the more extreme sensitivity combinations such as high load factor and low wind speed, resulting in more expensive electricity for VSDG systems. The VSDG hybrid system would not have been designed for these extremes, and therefore would not have been considered.

In Chapter 5, modelling of the system has been undertaken to investigate the operation of the VSDG in a hybrid system and to develop a control strategy. In the sub-transient model, no unwanted interactions occurred in the system and the control of power conversion for different generation through the inverter has been successfully simulated. In the power system dynamic model, the reduced performance of the VSDG, compared with constant speed operation, in maintaining stability under large load transients has been exposed. This led to the addition of a load level component, supercapacitors, in the variable speed hybrid power system. In order to assess more accurately possible real life fuel savings of the variable speed hybrid power system, actual renewable resources, along with a more detailed community load model, have been included into the power balance model. Over a 14 day simulation period, the resulting fuel savings for the fully variable speed hybrid system compared with the constant speed diesel generator with 32% minimum loading hybrid system has been calculated at 43%.

To help verify and further refine the hybrid system control strategy and uncover any unaccounted for real life interactions low, power experimentation has been carried out and is documented in Chapter 6. The test results show the correct operation and improved stability of the VSDG and Supercapacitor system to load steps and renewable generation fluctuations.

8.2 Conclusion

8.2.1 Contribution to Knowledge

In this research, a new hybrid system generator combination and integrated design has been investigated. This comprises of a VSDG integrated into a common DC-link renewable hybrid power system with central control of all components.

A control scheme for the fully integrated variable speed renewable hybrid power system has been designed and verified both through simulations and experimentation. This has, therefore, demonstrated that it is possible to successfully control different generators as desired (optimum, MPPT, etc) through DC/DC converters connected to a common DC-link. This allows a single inverter to be used, therefore negating the need for one inverter for each generator and thus reducing the cost of the complete hybrid system. Using a single inverter to supply a stand-alone grid also simplifies inverter control, as no grid synchronisation is needed. Therefore, no synchronisation timing is needed for the connection of the generators. Another benefit is that there can be no inverter-inverter interactions.

During computer simulations, the reduced transient performance of the VSDG compared with constant speed operation has been highlighted under load step charge or renewable generation output fluctuation. The need for a load levelling component to aid the VSDG under heavy load transients, which occur more often in renewable hybrid power systems, was apparent. After looking at all the possible load levelling components, supercapacitors have been chosen as the ideal device, because of their high power, reliability and ease of installation and use.
The effect of Supercapacitors on the stability of the system has been shown to be highly beneficial in maintaining DC-link voltage. This work suggests that the novel hybrid

power system will have reduced fuel consumption and overall lifetime costs compared to a conventional fixed speed wind-diesel hybrid system. Economic feasibility of any hybrid system can be quickly found given accurate renewable resource and load input data using HOMER.

In summary, the work in this thesis has contributed to knowledge of VSDG stability improvements and VSDG operation in a hybrid system in a number of ways. The potential problems of limited load step response when running VSDG at the most fuel efficient operating point has been demonstrated. A Supercapacitor load levelling system has been developed to work in harmony with the VSDG and hybrid system, as a solution to this problem. This has been shown to be more economical than compromising the optimal efficiency variable speed operation of the VSDG. It has also been shown that it is possible to fully integrate and control multiple generators connected to a communal DC-link.

Simulation of the resulting fully integrated variable speed hybrid system has been shown to reduce the cost of energy from 19.1p/kWh to 14.5p/kWh (Table 9) over the complete system lifetime, compared with a constant speed diesel in a hybrid system. Fuel consumption is reduced by 19-50% in the hybrid systems simulated in chapter 4 and 5. This gives a reduction in the energy CO_2 factor from 0.725 kg/kWh to 0.483kg/kWh (Table 10) which compares favourably with the UK delivered to site national grid average of 0.537kg/kWh.

8.2.2 Future Work

More extensive testing of the high power system should be carried out at the University of Edinburgh. The VSIG control could be altered to work in harmony with the supercapacitors, as demonstrated in the low power experimentation, instead of being a standalone unit, but this would require more collaboration with Cummins.

In the experiments, the wind turbine has been emulated and therefore is not completely accurate, especially in terms of the Maximum Power Point Tracking (MPPT). The testing of a prototype system with a real wind turbine input and DC/DC converter control would further validate the hybrid system control strategy.

There are wind turbines currently available that are capable of shedding power through controlled pitching of the rotor blades, so as to extract less power from the wind. They have been designed specifically for wind-diesel hybrid systems [30]. Implementing one of these wind turbines would allow long term energy storage to be omitted.

Ultimately, the commissioning of a long-term demonstrator project in an actual community would need to be carried out to assess real life impacts of the system both in terms of fuel savings and reliability.

References:

1. Consortium, S.S.W.I.I.S. *Muck Island*. [cited 17th Sept 2009]; Available from: http://www.smallwindindustry.org/fileadmin/ewea_documents/documents/projects/swiis/track_records/050511MUCKisland.pdf.
2. Leuchter, J., Bauer, P., Kurka, O., Hajek, V.: "*Efficiency investigation of mobile power sources with VSCF technology*", in International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2006 (SPEEDAM 2006)**,** 23-26 May 2006, Taormina, Italy, pages 475-480
3. "*Distributed Generation"*, IET factfile, 2008, www.theiet.org/factfiles
4. [cited 18th Sept 2009]; Available from: http://www.sparksdata.co.uk/refocus/fp_showdoc.asp?docid=22765750&accnum=1&topics=, *reFocus*. 2004
5. Singh, V., "*BLENDING WIND AND SOLAR INTO THE DIESEL GENERATOR MARKET"*, 2001, Renewable Energy Policy Project RESEARCH REPORT. p. 24
6. Koczara, W., Al-Khayat, N., Seliga, R., Al-Tayie, J., "*Variable speed integrated generating set an emerging technology for distributed power generation"*, in *IEEE Bologna PowerTech, Bologna, Italy, pt. 3, p 5 pp. Vol.3*. 2003.
7. [cited 18th Sept 2009]; Available from: http://dieselgenerators.co.uk/1500rpm.php
8. Hunter, R. and G. Elliot, "*Wind-Diesel Systems: A guide to the technology and its implementation"*, (1994: Cambridge University Press. 245.)
9. Manwell, J.F. and J.G. McGowan, "*Development of wind energy systems for New England islands"*, Renewable Energy, 2004. **29**(10): p. 1707.
10. Manwell, J.F., Stein W.A., Rogers A., McGowan J.G., "*An Investigation of variable speed operation of diesel generators in hybrid energy systems"*, Renewable Energy, 1992. **2**(6): p. 563
11. Carter, S., "*Emissions from Distributed Generation"*, 2000, California Energy Commission: California
12. McArthur, R.C., "*Development of a variable-speed generator driven by an internal combustion engine"*, Electronic Power Conditioning, Inc, 1990.
13. Al-Khayat, N., N. Jakeman, and W. Koczara, "*VSIG-variable speed integrated generating set for telecommunication application"*, in *23rd International Telecommunications energy conference (INTELEC), Edinburgh, Oct 14-18*. 2001.
14. Bumby, J.R., Brooking, R., "*An Integrated Engine-Generator Set with Power Electronic Interface for Hybrid Electric Vehicle applications"*, in *IEE International Conference on: Power Electronics, Machines and Drives, Bath, United Kingdom, Apr 16-18*. 2002
15. Rahman, M.A.; Osheiba, A.M.; Radwan, T.S.; Abdin, E.S., "*Modelling and controller design of an isolated diesel engine permanent magnet synchronous generator"*, IEEE Transactions on Energy Conversion, 1996. **11**(2): p. 324.

16. Hu, Y. and M. McCormick., "*A FPGA based fast DC link voltage controller for stand-alone diesel engine driven generator systems"*. Industrial Electronics Society, IEEE, 5-8 Nov 2002, 3, pages 1966-1973
17. Chen, Z. and Y. Hu., "*A hybrid generation system using variable speed wind turbines and diesel units"*, Industrial Electronics Society, IEEE, 5-8 Nov 2002, 3, pages 2729-2734
18. *Technical Data Sheet*, [cited 18th Sept 2009]; Available from: www.newage-avkseg.com,
19. Bob Panora, K.D., "*Small Engine Premium Power CHP"*, in 2nd Annual Advanced Stationary Reciprocating Engines Conference, 2005. Diamond Bar, California.
20. Elliott, D.L., C.G. Holladay., W.R. Barchet., H.P. Foote., W.F. Sandusky, "*Wind Energy Resource Atlas of the United States"*, (Solar Energy Research Institute 1986: National Renewable Energy Laboratory)
21. Sebastian, R. Castro, M. Sancristobal, E. Yeves, F. Peire, J. Quesada, J. *Approaching hybrid wind-diesel systems and controller area network*. 2002.
22. Cardenas, R. Pena, R. Clare, J. Asher, G., "*Power smoothing in a variable speed wind-diesel system"*, Power Electronics Specialist Conference (PESC'03), 15-19 June 2003, 2, pages 754-759
23. Ruin, S., Carlson,)., "*Wind-hybrid systems with variable speed and DC-link"*, Wind Power for the 21 Century, Germany, 25-27 September 2000.
24. Margaret Spillane, J.D. "*SIZING TECHNIQUES FOR STAND ALONE PV-WIND HYBRID RENEWABLE ENERGY SYSTEMS WITH STORAGE"*. in University Power Engineering Conference (*UPEC* 2005). University College Cork, Southern Ireland.
25. Ebert, P.R. and J. Zimmermann., "*Successful high wind penetration into a Medium sized diesel grid without energy storage using Variable speed wind turbine technology*" in *European Wind Energy Conference*. 1999. Nice, France.
26. Saramourtsis, A.C.; Bakirtzis, A.G.; Dokopoulos, P.S.; Gavanidou, E.S., "*Probabilistic evaluation of the performance of wind-diesel energy systems"*, Energy Conversion, IEEE Transactions on, 1994. **9**(4): p. 743.
27. Dokopoulos, P.S., A.C. Saramourtsis, and A.G. Bakirtzis, "*Prediction and evaluation of the performance of wind-diesel energy systems"*, Energy Conversion, IEEE Transactions on, 1996. **11**(2): p. 385.
28. A. L. Rogers, J. F. Manwell, J. G. McGowan, A. F. Ellis, "*Design requirements for medium-sized wind turbines for remote and hybrid power systems"*, Renewable Energy, 2002. **26**(2): p. 157.
29. Ruin, S., "*New wind-diesel system on Osmussaare"*, Wind Engineering, 2003. **27**(1): p. 53.
30. Sherif, S.A., F. Barbir, and T.N. Veziroglu, "*Wind energy and the hydrogen economy-review of the technology"*, Solar Energy, 2005. **78**(5): p. 647.
31. Ladakakos, P.D., M.G. Ioannides, and M.I. Koulouvari. "*Assessment of wind turbines impact on the power quality of autonomous weak grids"*, 8th International Conference on Harmonics and Quality of Power, 14-18 Oct 1998, 2, pages 900-905

32. [cited 18th Sept 2009]; Available from: http://www.distributed-generation.com/technologies.htm
33. Westlake, A., "*Modelling, Dynamics and Control of a Permantent Magnet Generator for Wind Power Application", PhD Thesis*, University of Durham, 1996, p. 291.
34. Rauh, A. and W. Seelert, "*BETZ OPTIMUM EFFICIENCY FOR WINDMILLS", in Applied Energy,* 1984, **17**(1), pages 15-23
35. [cited 18th Sept 2008]; Available from: http://www.enercon.de/en/_home.htm
36. *UK Wind Energy Resource: Wind Energy Fact Sheet 8*. 2005 [cited 18th Sept 2009]; Available from: http://www.berr.gov.uk/files/file17789.pdf.
37. "*Status of Electrical Energy Storage Systems"*, (DTI, 2004, Swanbarton Limited)
38. E.S.A. [cited 19th Sept 2009]; Available from: http://electricitystorage.org/technologies.htm.
39. "*Compressed air energy storage power plants"*, (F. Meyers, 2007, FIZ Karlsruhe)
40. [cited 2009 18th Sept]; Available from: http://www.mpoweruk.com/alternatives.htm.
41. *Types of Fuel Cells*. [cited 18th Sept 2009]; Available from: http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html.
42. Christopher P. Garcia, B.-j.C., Donald W. Johnson, David J. Bents, Vincent J. Scullin, Ian J. Jakupca, "*Round Trip Energy Efficiency of NASA Glenn Regenerative Fuel Cell System"*, (NASA, 2006, p. 13)
43. Rufer, A., "*Solutions for storage of electrical energy", z*ionamenti elettrici : Evoluzione Tecnologica e Problematiche Emergenti, Bressanone, Italy, 23-26 March 2003
44. Little, M., Thomson, T., Infield, D., "*CONTROL OF A DC-INTERCONNECTED RENEWABLE-ENERGY-BASED STAND-ALONE POWER SUPPLY"*, in University Power Engineering Conference (*UPEC*. 2005), University College Cork, Southern Ireland.
45. Kavadias, K.A.K., J. K., "*Storage system evaluation for wind power installations"*, in *Wind Power for the 21st Century*. 2000. Kassel, Germany.
46. R. Largent, M. Skyllas- Kazacos and J. Chieng, "*Improved PV System Performance using Vanadium Batteries*", Proceedings IEEE, 23rd Photovoltaic Specialists Conference, Louisville, Kentucky, May 1993.
47. M. Nakajima, M. Sawahata, S. Yoshida, K, Sato, H. Kaneko, A. Negishi and K. Nozaki, Denki Kagaku, "*Vanadium Redox Flow Battery with Resource Saving Recycle Ability. In Production of Electrolytic Solution for Vanadium Batteries from Boiler Soot*", In Denki Kagaku Oyobi Kogyo Butsuri Kagaku, 1998, Vol 6, pages 600-608
48. T. Kuntz, M. VRB Power Syst. Inc., "*Flow Battery Storage Application with Wind Power*",Transmission and Distribution Conference and Exhibition, Dallas, Texas (2005/2006 IEEE PES), 21-24 May 2006, On page(s): 937-939
49. Chacra, F.A., Bastard, P., Fleury, G., Clavreul, R., "I*mpact of Energy Storage Costs on Economical Performance in a Distribution Substation*", IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 20, NO. 2, MAY 2005

50. Little, M., M. Thomson, and D. Infield. "*Control of a DC-interconnected renewable-energy-based stand-alone power supply"*, in Universities Power Engineering Conference. 2005. Cork.
51. Taylor, P. and N. Jenkins, "*The development and application of distributed fuzzy load control to an autonomous wind diesel system",* in *Wind Power for the 21st Century*. 2000. Kassel, Germany.
52. Ribeiro, P.F., B.K Johnson, M.L. Crow, A. Arsoy, Y. Liu, "*Energy storage systems for advanced power applications",* Proceedings of the IEEE, 2001. **89**(12): p. 1744.
53. Hall, P.J. and E.J. Bain, "*Energy-storage technologies and electricity generation",* Office of Science and Innovation.
54. Ichinose, A., Aki, S., Kasahara, H., Sakaki, H., Ishiyama, A., Maruyama, A., Shimizu, N., Abe, H., Koso, S., "*Research and development of high-Tc SMES",* IEEE Transactions on Applied Superconductivity, 2005. **15**(2 PART II): p. 1947.
55. Nomura, S., Y. Ohata, T. Hagita, H. Tsutsui, S. Tsuji-Iio, and R. Shimada, "*Wind Farms Linked by SMES Systems",* Applied Superconductivity, IEEE Transactions on, 2005. **15**(2): p. 1951.
56. Srithorn, P., N.Y.A Shammas, S.B. Temakoon, and M. Aten. "*Testing of a super capacitor module",* in Universities Power Engineering Conference. 2005. Cork.
57. *The Project*. [cited 18th Sept 2009]; Available from: http://www.windandsun.co.uk/projects_foula.htm.
58. econnect. *Foula Community Electricity Scheme - operating results November 2007*. [cited 18th Sept 2009]; Available from: http://www.windandsun.co.uk/Data%20Sheets/Foula%20Report%20by%20Econnect%20Nov%202007.pdf.
59. [cited 18th Sept 2009]; Available from: http://www.dti.gov.uk/renewables/technologies/windspeed/online.html, *UK Windspeed Database*. April 2006.
60. [cited: August 2009] http://www.provenenergy.co.uk/windturbines_why_production.php
61 Yigzaw G. Yohanis , Jayanta D. Mondol, Alan Wright and Brian Norton**,** "*Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use",* Energy and Buildings, 2008. **40**(6): p. 1053.
62. Lambert, T. *HOMER help Economic Inputs*. 2004 [cited 2008 18th Sept]
63. Slootweg, J.G. and W.L. Kling, "*Modelling wind turbines for power system dynamics simulations: An overview",* Wind Engineering, 2004. **28**(1 SPEC ISS): p. 7.
64. Slootweg, J.G. and W.L. Kling, "*Modelling wind turbines in power system dynamics simulations"*, 2001. Vancouver, BC, Canada: Institute of Electrical and Electronics Engineers Inc.
65. Slootweg, J.G., de Haan, S.W.H.; Polinder, H.; Kling, W.L., "*General model for representing variable speed wind turbines in power system dynamics simulations",* IEEE Transactions on Power Systems, 2003. **18**(1): p. 144.

66. Wu, W.; Ramsden, V.S.; Crawford, T.; Hill, G., "*Low-speed, high-torque, direct-drive permanent magnet generator for wind turbines"*, 2000. Rome, Italy: Institute of Electrical and Electronics Engineers Inc., Piscataway, NJ, USA.
67. Petru, T. and T. Thiringer, "*Modeling of wind turbines for power system studies"*, IEEE Transactions on Power Systems, 2002. **17**(4): p. 1132.
68. Ryan, M.J. and R.D. Lorenz, *"Power-mapping' variable-speed control technique for a constant-frequency conversion system powered by a IC engine and PM generator"*, 2000. Rome, Italy: Institute of Electrical and Electronics Engineers Inc., Piscataway, NJ, USA.
69. Newborough, M.; Augood, P., "*Demand-side management opportunities for the UK domestic sector*", IEE Proceedings on Generation, Transmission and Distribution, Volume 146, Issue 3, May 1999 Page(s):283 - 293
70. *noabl wind speed database*. [cited 19th Sept 2009]; Available from: http://www.bwea.com/noabl/.
71. *Online Climate Data Directory*. [cited 19th Sept 2009]; Available from: www.ncdc.noaa.gov/oa/climate/climatedata.html.
72. *Department of Physical Geography: Automatic Weather Station*. Macquarie University, Australia [cited 19th Sept 2009]; Available from: http://aws.mq.edu.au/1min.php.
73. *Solar Energy - The UK's large solar energy resource*. [cited 19th Sept 2009]; Available from: http://www.solar-trade.org.uk/solarenergy/ukresource.htm.
74. Kusterer, J.M. *NASA Surface meteorology and Solar Energy*. [cited 19th Sept 2009]; Available from: http://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?uid=3030.
75. E.ON Climate and Renewables, Capital Grant Scheme for Offshore Wind, 3rd Annual Report, URN No: 08/P48. [cited 19th Sept 2009]; Available from: http://www.berr.gov.uk/files/file46398.pdf
76. [cited 19th Sept 2009]; Available from: http://www.batteryuniversity.com/parttwo-35.htm
77. from personal communication with Dr. Jim Bumby from the University of Durham School of Engineering
78. Andrews, David. "*Emergency diesel standby generators of Wessex Water potential contribution to dealing with renewable energy sources intermittency & variability"*, June 2007, **12**(3), The Institution of Diesel and Gas Turbine Engineers
79. from personal communication with Dr. Charles Cresswell from the University of Edinburgh, Institute for Energy Systems
80. [cited 25th April 2010]; Available from: www.nrel.gov/homer/

Appendix A

Eurosolare data sheet

PL 800 PolyCrystalline Si solar panel by Eurosolare

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manufacturer Eurosolare
nominal efficiency 10.6 %
nominal power rating 72 Watt
max voltage 600 Volt

Electrical characteristics during Standard Test Conditions (STC)

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voltage at OC 21.2 Volt
current at SC 4.5 Amp
voltage at MPP 17.2 Volt
current at MPP 4.2 Amp
δV/C° -77 mVolt/C°
δI/C° 1.2 mAmp/C°
tolerance +ve 7 % tolerance -ve 7 %

Electrical characteristics during load conditions (25 C°, 300 W/m²)

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voltage at OC 18.429 Volt
current at SC 1.35 Amp
voltage at MPP 15.699 Volt
current at MPP 1.26 Amp

Material characteristics

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incidence coefficient *(θ)* 95 %
specific heat capacity 920 J/kg/°C
absorption coefficient *(α)* 70 %
emission coefficient *(ε)* 85 %

Mechanical characteristics

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length 1215 mm width 555 mm thickness ? mm weight 8.5 kg