DC electrical interconnection of renewable energy sources in a stand-alone power system with hydrogen storage

This item was submitted to Loughborough University’s Institutional Repository by the/an author.

Additional Information:

- A Doctoral Thesis. Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University.

Metadata Record: https://dspace.lboro.ac.uk/2134/25757

Publisher: © Matthew Little

Rights: This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at: https://creativecommons.org/licenses/by-nc-nd/4.0/

Please cite the published version.
| University Library
| Author/Filing Title | LITTLE M |
| Class Mark | T |

Please note that fines are charged on ALL overdue items.

FOR REFERENCE ONLY
DC Electrical Interconnection of Renewable Energy Sources in a Stand-Alone Power System with Hydrogen Storage

By
Matthew Little

A Doctoral Thesis
Submitted in partial fulfilment of the requirements
for the award of
Doctor of Philosophy of Loughborough University
September 2006

© by Matthew Little 2006
Abstract

Many communities around the world have no access to an electricity grid. To supply power to these people, stand-alone power systems are often used, the majority of which are based on diesel generators. Rising fuel costs and environmental concerns make the use of renewable energy in stand-alone systems increasingly attractive.

The research reported in this thesis was to demonstrate a stand-alone power system based exclusively on renewable energy sources. To achieve this, a DC electrical backbone is used. Power electronic converters are used to interconnect the loads and generators and hydrogen is used as an inter-seasonal energy store.

The design and control of the DC based stand-alone power system forms the primary focus of this research.

A demonstration system has been implemented at West Beacon Farm in the UK. Substantial data has been collected that confirms the successful operation of the system.

Keywords: Stand alone power system, renewable energy, hydrogen.
<table>
<thead>
<tr>
<th>11.2 Economic analysis</th>
<th>173</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.2.1 Comparison with current stand-alone solutions</td>
<td>174</td>
</tr>
<tr>
<td>11.2.2 Comparison with AC system</td>
<td>174</td>
</tr>
<tr>
<td>11.2.3 Comparison of storage systems</td>
<td>175</td>
</tr>
<tr>
<td>11.2.4 Summary of economic analysis</td>
<td>176</td>
</tr>
<tr>
<td>11.3 Lessons learned</td>
<td>177</td>
</tr>
<tr>
<td>11.3.1 DC interconnected systems</td>
<td>177</td>
</tr>
<tr>
<td>11.3.2 West Beacon Farm system</td>
<td>177</td>
</tr>
<tr>
<td>11.4 Further work</td>
<td>178</td>
</tr>
<tr>
<td>11.4.1 DC interconnected systems</td>
<td>178</td>
</tr>
<tr>
<td>11.4.2 West Beacon Farm system</td>
<td>180</td>
</tr>
<tr>
<td>12 Conclusion</td>
<td>185</td>
</tr>
<tr>
<td>12.1 Original contribution</td>
<td>185</td>
</tr>
<tr>
<td>12.2 General conclusions</td>
<td>186</td>
</tr>
<tr>
<td>13 Acknowledgements</td>
<td>188</td>
</tr>
<tr>
<td>14 Glossary of terms and abbreviations</td>
<td>189</td>
</tr>
<tr>
<td>15 Publications by the author</td>
<td>190</td>
</tr>
<tr>
<td>16 References</td>
<td>191</td>
</tr>
<tr>
<td>17 List of Figures</td>
<td>197</td>
</tr>
<tr>
<td>18 List of Tables</td>
<td>200</td>
</tr>
<tr>
<td>19 Appendices</td>
<td>201</td>
</tr>
</tbody>
</table>
1 Project Overview

Stand-alone power systems are widely used in remote communities where either national grids don't exist or it is not economic to connect to the national network, and are especially common in the developing world [1]. The vast majority of such systems use diesel generators as the source of generation [2].

The use of renewable energy within these systems is growing due to a combination of rising fuel prices and environmental concerns [3]. Whereas diesel generation is on-demand, the output from wind and solar generation is dependant upon the temporal characteristics of the resource.

In the past renewables have been incorporated into diesel-based systems but generally at low penetration with an associated heavy reliance upon the diesel generator [4]. In order to facilitate a high penetration of renewables some form of energy storage is generally required. In very small-scale systems, batteries are commonly used, but for larger systems, hydrogen energy storage, when commercially developed, may be more appropriate.

1.1 Electrical interconnection options

Excepting very small battery systems (Figure 1-1a), virtually all power systems are based on AC that is held at nearly constant voltage and frequency (Figure 1-1b).

Rapid variations in the output from renewables can lead to excessive voltage and frequency variations. This can limit the penetration of renewable energy sources into power systems.

To increase the renewable energy penetration, a DC interconnected system was selected (Figure 1-1c), with the voltage and frequency requirements of the loads and generators made independent through the application of power electronic converters. In principal, this should allow higher levels of renewable generation whilst improving power quality.
1.2 West Beacon Farm system

West Beacon Farm, near Loughborough, Leicestershire, in the UK, has operated AC grid-connected wind, solar photovoltaic (PV) and hydro generators for many years. The system supplies various single and three-phase loads at the farm site, which includes a domestic residence, an office and a helicopter hangar.

A hydrogen energy storage system, comprising an electrolyser, hydrogen store and fuel cells, has been recently installed. This had been designed and implemented as part of the Hydrogen and Renewables Integration (HaRI) project, which has formed the basis of a number of research projects [5, 6].

As part of the research for this thesis, the equipment installed at West Beacon Farm was connected through power electronic converters to a DC busbar and loads supplied from this through power electronic inverters. This enables the system to operate stand-alone with a high level of renewable energy penetration. An overview of the final system design is shown in Figure 1-2.
Figure 1-2. Overview of the installed stand-alone power system.

The wind turbines supply the bulk of the energy to the system. The solar PV and the hydro systems also contribute significant generation. Power converters are used for connection of these sources due to their differing voltage and frequency characteristics.

There are a number of loads on the system, including motors, industrial three-phase devices and domestic single-phase equipment. Separate converters (inverters) are used to supply these.

Long-term energy storage is provided by a hydrogen energy storage system. The electrolyser and the fuel cells within the storage system are both connected through power converters.

A battery bank provides short-term storage. This directly couples onto the DC interconnection, i.e. without power conversion.

As this is a research project, there are times when equipment may be taken off-line for development or testing. In order to provide reliable power to the farm, a back-up grid connection from the national grid is included. One objective of the demonstration
was to show that the grid could be disconnected without upsetting the operation of the system.

1.2.1 Power converters

The aim of any power system is to provide acceptable power quality. Power quality tends to be reduced as wind energy penetration increases into stand-alone systems based on diesel generators.

The use of DC interconnected power converters may help provide better power quality since the voltage and frequency requirements of the loads are buffered from those of the generators. This separation should facilitate an increased penetration of wind energy into the system.

Both AC and DC interconnection systems require power converters to interface particular components, including:

- Electrolyser
- Fuel cell
- PV arrays
- Motor soft starts

Not too many additional converters are required for the DC connection system and so the cost of such a system, although more expensive than the more conventional arrangement in this regard, should not be excessive.

For the rotating prime movers, such as the wind turbines, the use of DC-interconnected power converters also:

- Allows variable speed operation
- Allows soft starting
- Removes the need for synchronisation

A further advantage of splitting up the loads on the system is that non-critical loads can be deferred to times when excess power is available.

1.2.1.1 Standard industrial drives

The general arrangement of the DC interconnection system is similar to some industrial systems where multiple motors are connected together through power electronic AC-DC converters, called ‘drives’. They are low cost, reliable and readily
available, due to the very large industrial market for such devices. These converters connect the AC devices to the system.

The DC generation sources such as PV require DC-DC converters that are more challenging.

1.2.2 System control

The challenge for the control system is to maintain the DC voltage on the busbar within design limits. The battery's role is to provide short-term stability. Longer-term stability is provided by the controllable elements: the electrolyser and the fuel cells.

1.3 Project aims

The main project aim is to implement and demonstrate the DC interconnection concept for a renewable energy based stand-alone power system.

The key specific tasks associated with this are:

- Design full system block diagram
- Specify all converters required
- Design and build DC-DC converters
- Install and commission the equipment
- Design and implement overall system control
- Collect performance data
- Ensure safe operation of the system (with particular regard to DC voltage level)

1.4 Summary of conclusions

Successful operation of most components has been demonstrated, proving that a DC interconnected stand-alone system based on renewable sources is feasible.

The system is currently more complicated than originally conceived. A number of different devices were required from a number of different manufacturers. Some were the only units commercially available, such as the fuel cells, and, as such, had not been designed for interconnection as shown here. Therefore, the connection and
interfacing of these devices required bespoke circuitry. The over-complexity of the system has affected reliability.

Numerous DC-rated switches and contactors were required and, because such devices must be physically larger to break the arc formed, as the direct current does not cross zero, along with the fact there is a more limited market for such devices, these were more expensive than similar AC-rated units. Thus, overall the system was more expensive to implement than initially estimated.

DC interconnection, as demonstrated in this project, could be used for remote stand-alone systems, although only after more research is undertaken aimed at a simplified and more reliable power electronic interfaces and the development of a commercial system controller. As a means of connecting rotating machines, the configuration proved very effective and with more standardisation to reduce system complexity, could be commercially attractive. Commercial DC-DC converters with high conversion ratios at significant power levels are not available and the bespoke designs were developed and demonstrated as part of the research. Serial or mass-manufacture of these important components would significantly reduce the cost of these and improve their reliability.

It was found that the electrolyser installed was poorly suited to the demands of the system. In particular, it was unable to follow accurately the variations in renewable energy supply and could not be operated at low power. Control approaches were developed to work around these limitations but with only partial success. The development of electrolyzers that are more appropriate for use with renewable energy sources is urgently required.
2 Technology review

2.1 Stand-alone power systems

It is estimated that 1.6 billion people worldwide do not currently have access to an electricity grid [1] and the majority of these people live in rural areas of the developing world [1, 7-9]. In addition, many rural and isolated communities within the developed world, such as small islands, do not have access to a national grid [10]. In the past, national electrification projects have tended to concentrate on densely populated areas due to the infrastructure cost of connecting sparse and remote communities [11].

The alternative to a large electrical grid is to use a stand-alone network to supply electricity to local consumers from locally installed generation capacity [12, 13]. Depending upon the size of load and the distance to the national grid, there is a point at which a stand-alone system becomes economic [13].

There is no clear distinction between a national grid and a large stand-alone power system. For the purposes of this thesis, stand-alone power systems are in the region of a few hundred watts up to hundreds of kilowatts of capacity.

Stand-alone systems can have lower investment costs, due to the reduced infrastructure requirements [12], but may prove expensive in the long term due to fuel and maintenance costs.

2.1.1 Renewable energy use in stand alone power systems

The majority of stand-alone power systems use diesel generators [2]. There are increasing economic and environmental problems with dependence upon this fossil fuel resource, so the use of renewable energy is seen as a better solution [3].

Renewable energy resources are inherently distributed and usually some form is locally available. Using renewable energy will buffer the community against the increasing cost of fossil fuels. In the long term, this can make economic sense, as the higher capital cost will be compensated for by the reduction, or even absence, of expenditure on fuel.
2.1.1.1 Penetration

Energy penetration of a generator within a system is the annual energy produced by the generator as a percentage of the gross electricity consumption [14]. The ability for a power supply system to cope with a variable resource, such as renewable energy, is affected by the penetration of the resource into the system. The technical and economic concerns of increasing penetration of renewable energy into a power system are explained in the following sections.

2.2 Matching supply and demand

In any power system, the demand must be met instantaneously [15]. The demand on a power system will vary with time, following the requirements of the consumer. Most renewable generation varies with the available resource. This leads to a mismatch between supply and demand.

![Mismatch between renewable energy supply and demand.](image)

In order to ensure demand is met, a power system can:

- Control generation to match demand
- Use energy storage
- Control demand

These techniques can be used individually or in combination.
2.2.1 Aggregation

Aggregation is very important to the design and operation of power systems. Individual loads are to an extent independent, especially when short-term variations are considered. Different renewable energy sources also vary independently in time and are not generally correlated with the loads they supply. The different time characteristics can thus be viewed as random. Figure 2-2 shows that when randomly varying time series are aggregated the result shows less variability.

![Figure 2-2. Aggregation of random signals.](image)

Within large interconnected power systems, such as a national grid, a large number of loads are aggregated and hence variations in the overall power requirement are relatively small. This eases the control requirements.

With fewer loads, the relative variation in demand becomes greater. Aggregation also applies to variable generators such as renewables. In a stand-alone power system, the relative variations of both supply and demand are greater, making operation much more difficult than large inter-connected grid systems [15].

2.2.2 Load control

Loads can be controlled in order to help match supply with demand. Loads can be designated in terms of their importance and, if there is a deficit, are deferred in inverse priority order until times when there is a surplus of generation [16, 17]. These
are called ‘defferable loads’. There are usually critical loads that must always be supplied.

2.2.3 Energy storage

For reasons of local self-sufficiency, a high level of renewable energy penetration into a small power system is desirable. This cannot be achieved directly due to the high variability and low aggregation of loads and generators. Therefore, incorporating renewable energy into stand-alone power supplies usually requires some form of energy storage [15, 18, 19].

2.2.3.1 Variability characteristics

The variability characteristics of the loads and wind and solar energy generation, affect the characteristics of the required energy store.

2.2.3.1.1 Variability of loads

The load varies depending upon consumer demand. Critical loads must be supplied as required. The loading upon a system can vary on a very short time scale. Figure 2-3 shows an example of typical single-phase domestic loads over an hour.

![Figure 2-3. Typical single-phase domestic load variation [20].](image-url)
2.2.3.1.2 Variability of solar resource

The solar energy available at a particular location is highly predictable [21]. There are two main timescales of predictable variation: daily variation deriving from the rotation of the earth about its axis, and inter-seasonal variation due to the tilt of the earth relative to the sun's orbit. The main unpredictable factor affecting solar radiation is the varying cloud coverage of the sky.

2.2.3.1.3 Variability of wind resource

Research has shown that wind energy varies over a number of different timescales [22]. For the control of a stand-alone power system, the most important are the second to second variations, due to gusts in the wind and known as turbulence. Wind energy also has an inter-seasonal variation that needs to be taken into account in the design of wind supplied stand-alone systems.

2.2.3.2 Energy storage characteristics

The store must be able to supply the short-term variations to cope with, for example, wind turbulence. The energy store may also be required to cover inter-seasonal variation.

Efficient long-term energy storage is the key to a renewable energy based stand-alone power supply. This is difficult to achieve and to date no successful schemes have been demonstrated.

2.3 Electrical interconnection systems

Two separate electrical power systems, DC and AC, were promoted at the turn of the nineteenth century.

2.3.1 Direct DC interconnection

One method, supported by Thomas Edison, was the use of direct current (DC) to transmit power from generators to the consumer.
In a direct DC system, the voltage generated is the voltage used by the consumers throughout the whole system and hence must be quite low. At low voltages, high currents must flow to supply the same power and hence resistive losses are higher. For this reason, such systems cannot transmit power over long distances. Mechanically complicated, and hence expensive, DC machines were required.

2.3.2 AC interconnection

Others, including Nikola Tesla, saw advantages in using alternating current (AC) for transmission of power.

The use of AC within large power systems has a number of advantages. It can easily be stepped up and down through a transformer. This allows higher voltages to be used for the transmission system, while supplying customers at lower voltages. At higher voltages, the current and hence the resistive power loss and voltage drop are
lower, allowing long distance transmission. Cheap, simple and reliable motors (mainly induction motors) can easily be driven from an AC supply.

For these reasons, the vast majority of large interconnection schemes, including all national-scale grids, are AC based.

2.3.3 Quality of supply

Power quality can be defined as 'voltage and frequency stability together with the absence of various forms of electrical noise' [23]. Quality of supply is a measure of how closely supply and demand are balanced. Within an AC system, the voltage and frequency are indicators of the quality of supply. Within a DC system, the voltage level is the indicator.

Most equipment is designed to run from a fixed frequency, fixed voltage supply. A power system must provide a voltage and frequency that is of good enough quality to supply these requirements.

The sensitivity of a load to the quality of supply varies. For example, a resistive heating element is very tolerant of supply disturbances and functions even with a relatively low quality of supply, whereas medical equipment might be very sensitive to the quality of supply [24].

2.3.3.1 Reliability

If the power quality is very low, the voltage and frequency may not be in the range required for correct operation of the equipment and the power system is unreliable. Decreasing reliability is the outcome of very poor power quality.

The total cost of system reliability is a combination of the investment cost in equipment to improve reliability (higher with increased reliability) and the associated cost of interruptions to the consumer (lower with increased reliability) [25]. The appropriate system reliability is when the total cost is at a minimum. Achieving very high reliability is expensive in a large national system but is even more expensive in a small system [26].

A stand-alone system must supply a reasonable quality of supply, and hence good reliability, although it would be very costly to match that of a national-scale grid.
2.4 Typical stand-alone systems

Several systems used to supply stand-alone communities are discussed in this section.

2.4.1 Diesel generators

Small power systems based on diesel generator sets are by far the most common [2]. They require a ready supply of diesel fuel and are run whenever power is required, or sometimes according to a pre-defined time schedule. They are generally sized to supply at least the peak load on the system and are commonly available with power outputs from a few to hundreds of kilowatts. They are used extensively as they provide acceptable reliability at very low initial cost. An example is described in [27].

Problems with the use of diesel generators include:

- Cost of fuel and its transportation [27, 28]
- Local environmental effects, such as the reduction of local air quality [3]
- Global environmental effects, such as climate change [3]
- Security of fuel supply [29]
- Inefficient when partially loaded [27, 28]
- Start-up response time [23]
- Noise [29]
- Require a high level of maintenance [27].

Diesel-based systems typically use an AC interconnection. This allows easy connection of rotating generators and loads, but there must be synchronisation between the generators, the loads and any storage device, which is difficult to achieve in practice.

2.4.2 Wind-diesel systems

Wind turbines have been added to many diesel-based systems in order to reduce the fuel consumption. Examples in the range of one to thirty kilowatts are discussed in references [4, 30-33].

Many such systems require that the diesel generator runs constantly and therefore fuel savings are limited. More sophisticated systems allow the diesel engine to be
turned off when there is ample wind. Controlled dump loads are used to balance the supply and demand and flywheels can help smooth the short-term fluctuations [34, 35].

Despite years of development effort, the penetration of wind energy is low, with typical penetration levels only up to 25% [4, 23], and systems still rely heavily upon the diesel generator. No commercially attractive wind diesel systems with high wind penetration have been proven, although many aid supported demonstrations systems have been deployed over the last decades [23].

2.4.3 PV, wind and lead-acid batteries
Lead-acid batteries are often used in very small power systems supplied by PV, wind or both [8, 36, 37]. Systems using mixtures of solar PV and wind can have the advantage of the different inter-seasonal variability complimenting each other [38, 39].

The lead-acid batteries must be carefully maintained to ensure reasonable lifetimes [40]. To do this a charge controller is nearly always required [41], which will dump any excess power and disconnect the load if the battery is at a low state of charge.

Small battery-based systems nearly always use a direct DC connection [41], which allows direct connection of the battery and some DC devices. Due to the differing voltage levels, attaching a number of different DC devices is problematic usually requiring some form of power converter. In order to power AC devices a power electronic inverter is required [41, 42].

The renewable resource varies inter-seasonally, but lead-acid batteries cannot store energy over this period [43]. Their short-term energy storage and restricted charge rates limit the size of such systems [40]. Typically, they range in size up to a couple of kilowatts.

2.4.4 Micro hydro systems
There are many stand-alone hydropower systems supplying small communities and which are ideal wherever the resource is available [44].
Mechanical control of the water flow can be used to provide the power balance, but in very small systems, it can be more economic to use an electronically controlled dump load.

Micro hydro systems are in the range of a few hundreds of watts up to several kilowatts [45]. Usually, such systems can only be used if there is a locally available resource and their costs are usually dominated by the civil engineering work required.

An interesting pumped hydro storage scheme has been developed on the island of Gran Caneria, where it is used to help incorporate wind energy into a stand-alone system [46].

2.4.5 Conclusion
The stand-alone power systems outlined here all have limitations and, in the vast majority of cases, the long-term penetration of renewable energy sources is low, in most cases less than 25% [23].

To increase this, the supply and demand must be better matched. If renewable energy sources predominate, generation is not fully controllable, although there is always the possibility of curtailing output. Critical electricity demands must be met, so the scope for load control is limited and it cannot be relied upon to match supply and demand. To increase the level of renewable energy penetration therefore requires some form of energy storage [19, 23].

2.5 Energy storage options
The main forms of energy storage are presented here.

2.5.1 Lead Acid Batteries
Lead-acid batteries store energy in the form of chemical energy using a reversible reaction. They are comprised of lead electrodes within a dilute sulphuric acid electrolyte. They are used extensively in many devices, as they are relatively cheap and easily obtainable. The easy addition of battery storage was an argument for using direct DC interconnection in early power systems, such as those promoted by Edison.
Problems with lead-acid batteries include:

- **They self-discharge at a rate of 1-5% total energy per day** [47, 48]  
  This means they are only practical for short-term energy storage.

- **Temperature affects both capacity and lifetime** [40, 49]  
  A large number of stand-alone systems are installed in the developing world, where temperatures are generally higher. The battery lifetimes are generally lower which increases the associated system cost. In colder climates, the battery capacity is reduced.

- **Capacity is dependant upon current** [40, 48]  
  Much larger stores are required with increasing amounts of generation or load.

- **Lifetime is dependant upon discharge cycles and depth of discharge** [48, 49]  
  Larger stores are required to ensure reasonable lifetimes and only partial use of full nameplate capacity can be made [40, 41].

- **Their storage density is approximately 30 to 40 Wh/kg** [50]  
  In comparison to diesel, with an energy density of 11600 Wh/kg [51], a lead-acid battery store will be very large.

- **A periodic equalisation charge is required** [48]  
  This increases maintenance costs.

- **Lead acid batteries cost around £40 per kWh** [52]  
  Although this is low, the technology has been around for over 100 years and there is little potential for cost reduction.

Often cheap car batteries with lead sponge plates are used rather than deep-cycle batteries especially designed for stand-alone operation which exacerbates these problems [40, 41].

### 2.5.2 Other battery technologies

There are some promising new battery technologies appearing on the market, including:

- Nickel cadmium [50]
- Nickel metal hydride [50, 52]
- Lithium ion [50, 52]
- Sodium sulphur [53, 54]
• Sodium nickel chloride [55]

The first three technologies are room temperature devices; the last two work at high temperatures and must be enclosed and heated.

These batteries solve some of the problems associated with lead-acid batteries but they have not been taken up quickly due to their comparatively high cost [50].

All of these technologies have long-term potential for cost reduction through mass manufacture.

2.5.3 Flywheels

The energy stored in a flywheel is proportional to the inertia and the square of the rotational speed.

Traditional flywheels are attached to standard electrical machines directly connected to a 50 (or 60) Hz power system. This limits the speed to 3000 (or 3600) rpm. Extracting the stored energy is achieved through a speed reduction and is limited by the allowable frequency range. In practice, these flywheels are big and only store energy for rapid changes, in the range of a few seconds [56]. Examples include [30, 34].

High-speed flywheels employ power electronics allowing the electrical machine to rotate at much higher speeds and allowing the speed to vary independent of the system frequency. Thus, they are much lighter and more compact.

Practical problems with increasing the rotational speed include stress on the components, friction losses of the bearings and safety issues due to the release of the energy if the wheel were to break loose.

At present, their practical energy storage time is in the order of seconds [56] and there are no known examples of high-speed flywheels being used with renewable energy.

2.5.4 Capacitors

Capacitors store energy in the form of an electric field. They are widely used for very short-term energy storage in the field of electronics.
Super-capacitors store electrical energy in the two series capacitors of the electric double layer, which is formed between each of the electrodes and the electrolyte ions. The capacitance and energy density of these devices is thousands of times larger than standard electrolytic capacitors [57]. Other types of super-capacitors are under development that also use pseudo-capacitance, which may achieve even higher energy density [58].

At present super-capacitors are very expensive and not economic for large capacity energy stores [43].

2.5.5 Hydrogen

The electrolysis of water into hydrogen and oxygen can be used to provide a chemical energy store [59]. The hydrogen is recombined with oxygen in a fuel cell to generate an electrical current. This is the hydrogen cycle shown in Figure 2-6, along with the chemical reaction equations.

\[ 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} \]

Three components are required for a hydrogen gas energy storage system: an electrolyser, some form of gas storage and a fuel cell. The electrolyser can be used as a controllable load through which excess energy is used to produce hydrogen gas. This can then be used to generate electricity in times of deficit through a fuel cell. Hydrogen can be stored indefinitely, which is a major advantage over most other storage systems.
Hydrogen has a density of 0.0899 kg/Nm$^3$ and has an energy density of between 3.0 kWh/Nm$^3$ (the lower heating value) and 3.5 kWh/Nm$^3$ (the higher heating value), where one Nm$^3$ is a normal meter cubed: the volume of the gas at standard temperature and pressure [51].

The energy capacity of the store is dictated by the physical size of the storage. Increasing the capacity of the energy store is relatively economical, once the electrolyser and fuel cell have been installed, through the addition of more tanks or by compressing the hydrogen gas.

The reaction within the fuel cell generates both heat and electricity in proportions of approximately 50% each [60]. Some of this heat can be captured and used.

As a relatively new technology with a large potential market, reductions in component cost should occur in the future [61, 62]. Reviews of hydrogen energy storage systems can be found in [5, 63]. State of the art stand-alone projects based upon hydrogen energy storage include wind-hydrogen systems on the Islands of Unst, UK [64] and Utsira, Norway [65].

Additional interest in hydrogen as a form of energy storage has been sparked recently due to its potential use as a transportation fuel with zero local pollution [66].

2.5.6 Flow cells

Flow cells work by combining two tanks of different electrolyte within a cell. An ion-selective membrane separates the electrolytes. A current is then generated by the cell, which powers the load. All the energy is stored within the electrolyte, rather than some in the electrolyte and some in the electrodes, as with other batteries [67]. The energy stored is therefore only limited by the amount of electrolyte stored. Regenysys, in Cambridgeshire, UK is one example [67].

2.5.7 Energy storage characteristics

In choosing a storage system, the time period over which the store can operate is a critical factor. This contributes significantly but not exclusively to the relative cost [43].

Figure 2-7 shows the cost per kWh against the storage period. At very low time scales (seconds to minutes), capacitors and flywheels are the most cost effective
solution, for mid range time scales (hours to days), batteries, such as sodium sulphur and nickel metal hydride, appear to be the best option.

\[
\text{Relative Cost of Increasing Storage Capacity Against Storage Time}
\]

![Graph showing cost against storage time for various technologies](image)

Figure 2-7. Cost against storage time for various technologies [43].

*(Data supplied and used with kind permission from John Barton)*

The main renewable resources, solar and wind, have a strong inter-seasonal variation and hence an energy storage method is required to ensure an annual energy balance. To do this, energy must be stored over timescales of months to a year. Over such time periods, hydrogen storage is the most economic.

### 2.6 Conclusion

In a stand-alone power system, the generation must match the demand at all times to ensure good power quality. High variability of the loads and the sources and low aggregation mean that, to do this, some form of energy storage system is required. Due to the inter-seasonal variation in the solar and wind resource, a hydrogen based storage system has been deemed the most appropriate.
Figure 2-8 shows the basic energy flows within such a system.

Figure 2-8. Basic renewable energy based stand-alone power supply.
3 West Beacon Farm system

A stand-alone power supply based on renewable sources and using hydrogen storage is considered feasible. A test system is required in order to validate this concept. By building a real system, technical and practical issues can be identified and addressed.

3.1 Background information

West Beacon Farm, near Loughborough, Leicestershire, UK, was used as the basis for a test system. It is the home of Professor Tony Marmont and his wife. Over the last fifteen years, a renewable energy generation system has been established at the farm, which has operated connected to the national grid [68]. The system supplies a residential building and a small set of offices. It incorporates solar thermal panels, photovoltaic generators, wind turbines, run-of-river and lake-storage hydro systems and a heat pump, along with a lead acid battery bank and inverters. The supply to the buildings was buffered through a 120V DC lead acid battery bank and inverters. The wind turbines were direct-on-line AC grid-connected.

West Beacon Farm is located close to CREST, the Centre for Renewable Energy Systems Technology, part of the Electronic and Electrical Engineering Department at Loughborough University.
3.2 Map of the test site

Figure 3-1. Map of West Beacon Farm test site.
(Reproduced with kind permission from Rupert Gammon)
3.3 Previously installed equipment

Previously to this research, the following components had already been installed at West Beacon Farm.

3.3.1 Wind turbines

Two 25 kW rated two bladed stall-regulated induction-generator wind turbines, manufactured by Carter Industries, are installed. They include pitch-regulated over-speed protection. These are the main generators on the system and supply the bulk of the energy, approximately 15 MWh each annually. Their supplied controllers are designed for direct-on-line connection to a three-phase AC grid and they require a local supply of 110V AC to power the brake on the blades.

Figure 3-2. Installed wind turbines with close-up.

Figure 3-3 shows the power/speed and the torque coefficient/tip speed ratio graphs for the turbines.
3.3.2 Solar photovoltaic arrays

A fixed array of 6 kWpeak of photovoltaic modules is already in place. This is comprised of 3 kWpeak of monocrystalline modules, manufactured by Solarex, and 3kWp of polycrystalline modules, manufactured by ARCO. These were installed by SolarPac and have been split into 1.5 kWpeak arrays wired at 120 V DC nominal.

Three tracking arrays of 1 kW each are also installed. These pump water for the lake storage hydro system and are not directly connected to the electrical system.
Figure 3-4. Installed PV arrays (tracking and fixed).

3.3.3 Run-of-river hydro power system

A 1 kW cross-flow type hydro turbine, manufactured by Valley Turbines, UK, was installed by Dulas. This generates 3-phase wild frequency AC power from a river that flows through the grounds.

3.3.4 Lake-storage hydro power system

A 2.7 kW Turgo type hydro turbine runs from a storage lake generating single-phase wild frequency AC power. The turbine was manufactured by Energy Systems and Design, Canada and installed by Dulas.
3.3.5 TOTEM CHP unit

The TOTEM combined heat and power (CHP) unit comprises of an internal combustion engine, run on liquid petroleum gas, and a generator. It outputs 38 kW of heat and up to 15 kW of electrical power. The unit was supplied locally by John Knight.

3.3.6 Hydrogen storage system

A hydrogen based storage system had been designed and installed as part of other research carried out into the viability of a 'hydrogen economy', [5, 6]. This was connected to the AC electricity grid and was sized as an inter-seasonal store of
energy. The hydrogen storage system comprises the electrolyser, the hydrogen storage tanks and the fuel cells.

3.3.7 Electrolyser Specifications

The electrolyser is a high-pressure alkaline type, manufactured by Van Den Borre, a Hydrogenics company [69]. It is rated at 36 kW$_{\text{max}}$ and can supply 8 Nm$^3$/hr of hydrogen gas at 25 bar when run at rated power. This choice was limited by the small range of 'off the shelf' electrolysers available on the open market.

The electrolyser uses Inorganic Membrane Electrolysis Technology. It comprises two main units, the process unit and the electrical power supply unit. The process unit houses the stack, which is comprised of 46 individual cells. This requires a DC supply voltage of between 80 to 100 V at up to 440 A.

The quoted energy requirement to produce one normal meter cubed (Nm$^3$) of hydrogen in the process module is 3.9 kWh, against a theoretical minimum of 3.55 kWh. Added to this are additional losses from the gas driers, which increase the total to 5.2 kWh.

Figure 3-7. The installed electrolyser process cabinet with close-up of the cell stack.
3.3.8 Storage specifications

22.8 m$^3$ of storage tanks store the generated hydrogen, at up to 137 Bar. At this pressure, 2856 Nm$^3$ of hydrogen gas can be stored, equivalent to approximately 8 MWh of embodied chemical energy. BOC Gases have supplied the tanks, along with the associated pipe work, safety equipment and risk assessment.

In addition to the main store, a 37.8 litre buffer tank and a Hydro-Pac C03-05-2550LX-V compressor are connected to the output of the electrolyser. The compressor, as shown in Figure 3-8, includes a hydraulically driven intensifier and two gas chambers, one at each end. A 3.75 kW induction motor drives the hydraulic stage. The additional tank buffers the flow of hydrogen from the electrolyser to the compressor avoiding negative pressure problems. The compression ratio is 1:8 at a flow rate of up to 11 Nm$^3$/hr.

Figure 3-8. The hydrogen storage system.

Hydrogen is supplied from the main storage tanks, via a pressure reduction valve, to the fuel cells.
3.3.9 Fuel cells

The installed hydrogen storage system was designed as a test bed for hydrogen based technologies. To this aim, two fuel cells have been installed with space for a third. There was a very limited choice of available fuel cell units when the hydrogen storage system was designed. Hence, the sizing of both units was based mainly upon what was available, rather than on the specific requirements.
3.3.9.1 Intelligent Energy fuel cell

Intelligent Energy supplied one of the fuel cell systems [70]. This unit is based upon a proton exchange membrane (PEM) cell stack and is designed for combined heat and power generation. It is rated to supply a maximum of 2 kW of electrical power and 2 kW of thermal power. The stack voltage is between 25 and 50 V DC, depending upon the electrical power generated. This stack voltage is converted internally to 24 V DC. This recharges a small bank of sealed lead-acid batteries. This provides a buffer for the fuel cell operation so that instantaneous power can be drawn from the fuel cell unit.

3.3.9.2 Plug Power fuel cell

Plug Power, a GE company based in the US, manufactured the second system, also based upon a PEM cell stack [71]. This unit was designed as a remote supply for telecoms equipment. It does not have a facility to recover the heat generated in the stack. It is rated to supply a maximum electrical output of 5 kW, at 48 V DC. The stack voltage varies, depending upon the load applied, between 30 and 60V DC. This is converted internally to 48 V DC and recharges a small sealed lead-acid battery bank.
3.3.10 System consumption

Loads connected to the system include a single residential dwelling, a helicopter hangar and an office. Both single and three-phase supplies are available. The largest electricity-consuming load on the system is a three-phase induction motor that drives the heat pump. This is used to heat the house and consumes approximately 14 MWh annually. The heat pump comprises an induction motor powered compressor and heating and cooling loops. The cooling loop is installed at the bottom of a lake. When the pump runs, the system tries to cool down the lake by removing heat. The resultant heat energy is greater than the electrical energy required to run the compressor by a ratio of approximately 2.5 to 3.5.

Additional loads include the pump within a reverse osmosis rig, which is used to purify dirty water into drinking water.
The average load over the year of 2004 was approximately 2.34 kW, with a total consumption of over 20 MWh.

3.4 Summary

The main components of the system installed at West Beacon Farm have been introduced. Before this project, the wind turbines were operating grid connected and the main three-phase electricity loads at the farm supplied from the grid. The single-phase supply was buffered through a 120V DC lead-acid battery bank fed from the solar PV, hydro and a grid-connected battery charger.

These devices are to be reconfigured to work as an interconnected stand-alone power system.
4 Electrical System Design

It was decided that the installed equipment at West Beacon Farm would be re-configured electrically to form a stand-alone power system. The bulk of the energy supplied to the system will be from the two wind turbines. These use induction generators, which must be fitted with power electronic interfaces to be able to operate as stand-alone units.

The justifications and specific details of the electrical system design are presented in this chapter.

4.1 Interconnection system

4.1.1 AC interconnection

Traditionally a system of this size would be connected using an AC interconnection of the sort shown in Figure 4-1.

![Figure 4-1. AC based electrical system.](image-url)
In order to maintain reasonable power quality to the loads, the penetration of renewables into such a system is limited. To stop a large in-rush current, any induction generators, such as the wind turbines, must be synchronised with the AC busbar.

In addition, a number of components need some form of power conversion equipment to be connected to an AC system, due to their differing voltage ranges and operational characteristics. These are:

- Electrolyser
- Fuel cells
- Solar PV
  These are DC devices with non-linear current/voltage characteristics.
- Hydro generators
  These generate a variable-frequency AC waveform.
- Some rotating loads
  Power conversion equipment is required to perform a soft start on some of the motors and/or to allow them to run at a variable speed.

### 4.1.2 Power conversion-based DC interconnection

The aim is to increase the penetration of renewable energy into the power system. A system connected through power electronic converters on a central DC busbar appears to have the potential to achieve this aim. An overview of such a system is presented in Figure 4-2.
Figure 4-2. Electrical system using power converters and DC connection.

Power electronic converters are used to connect every device, both AC and DC, to a central DC busbar. The power electronic converter for the wind turbine must also supply reactive power to enable the induction generator to operate properly, i.e. to provide its excitation. The other system components, mainly the single and three phase supplies, must be supplied directly with an AC waveform of sufficient power quality.

The separation provided by the converters and DC link allows control over the specific voltages and frequencies, which should lead to higher renewable energy penetration whilst maintaining a reasonable power quality [15]. It also removes load and generator synchronisation problems and allows more independent individual component control.

4.1.2.1 Industrial DC systems

The connection of machines through power converters to a central DC busbar is similar to a number of industrial systems. Within these applications, such as mining and paper mill industries and some ship power supply systems, motors are
connected through power electronic converters onto a central DC busbar [72]. The busbar is connected through another converter to the AC grid.

Figure 4.3. Industrial DC-based system.

These systems are installed to allow precise control of the various motors. Energy, and hence money, is saved by allowing the various motors to run at different speeds/frequencies. The spinning motors can then be used, when not under load, as generators to feed power back to other motors [72].

4.1.3 Interconnection method comparison

It may seem that, with all the AC devices on the system, the use of a DC interconnection may not be the most appropriate solution. However, the number of power electronic converters required for the AC based system is similar to the DC system. Furthermore, the majority of devices require a number of different voltages internally and normally already have some form of built-in power conversion, for example, the hydro turbines generate a wild frequency AC that must be rectified and converted to the required voltage whether the interconnection system is AC or DC.

Although a DC connection may require slightly more power conversion equipment, it offers a degree of separation between the components. They can then operate at different speeds/frequencies without synchronisation problems. This is expected to help increase the penetration of renewable energy.
The cost of power electronic components has fallen dramatically within recent years, along with major advances in reliability and increases in efficiency [73]. This process is expected to continue and the DC interconnection design concept presented here may well become commercially attractive within a few years.

4.2 Electrolyser Operation

The electrolyser is the main controllable load on the system. The electrolyser stack is a low voltage, high current controllable DC load. Power conversion is required to connect the unit to the system. The electrolyser stack is comprised of cells, which must be supplied with a certain potential in order to electrolyse water molecules into hydrogen and oxygen. The current applied to the cell controls the rate of hydrogen production. The stack voltage is proportional to the number of cells. The IV characteristic for a typical electrolyser cell is shown in Figure 4-4. This is dependant upon process temperature and pressure, which both affect the efficiency [6, 47].

![Electrolysis Cell Current/Voltage Characteristic](image)

Figure 4-4. Typical I-V characteristic of an electrolyser cell [6].

4.2.1 Electrolysers with renewables

Research has been carried out into the use of electrolysers with renewable energy [6, 63, 64, 74-79]. The main conclusions from these studies include:

- Commercial units have been designed for steady state operation [5].
• System instability and reduced efficiency can occur due to the dynamic power input [78].
• When operated with rapid fluctuations the purity of the product gases is reduced [78, 80].
• The majority of these systems have smoothed the supply to the electrolyser using batteries or a grid connection [78].
• Power electronic converters are usually required to match the current and voltage characteristics of the generator and the electrolyser [78, 80].
• Temperature and pressure affect electrolyser operation and efficiency [6, 78, 80].

4.2.2 Limitations of electrolyser operation

To control the power in the system, an electrolyser with a fast response over a wide range of power levels is required [74]. There are several limitations to the operation of the electrolyser, some of which were only highlighted when the system had been installed and run at variable power levels.

Reasonable gas purity must be maintained. At low currents, this is not possible, as the impurities become an increasing percentage of the hydrogen production. Therefore, a limit must be set on the minimum current at which the unit is allowed to run. From discussion with the manufacturers, the range of operation was set to between 25 and 100 percent of the rated power.

In order to follow the incoming renewable resource, the electrolyser must be able quickly switch on and off. Problems with this were highlighted at an early stage. It is thought that when the electrolyser is switched off, hydrogen in the cathode causes the potential of the cell stack to reverse. This causes corrosion of the cell membranes and hence a reduced lifetime of the unit [6]. For this reason, the manufacturers placed a limit upon the number of on/off cycles for which they would guarantee the unit. They also installed a short time delay on start-up and shutdown operation to avoid rapid on/off cycling.

These two requirements mean that the cycling of the electrolyser should be minimised and, when switched on, a minimum current of 25% of the maximum rated current must be maintained.
This leads to the need for some form of additional short-term storage to cope with short-term variations, as the electrolyser cannot react quickly to the incoming energy fluctuations.

To ensure that the requirements of the electrolyser are met, a battery has been added to the system. This will allow the electrolyser to 'ride out' dips in the variable incoming power. This removes the need for instantaneous control of the electrolyser and fuel cells, as the battery will provide short-term smoothing.

While hydrogen is one of the only practical forms of long-term, inter-seasonal storage, batteries are an efficient form of short-term storage in timescales up to hours. A small amount of battery storage increases the overall system efficiency. It has been found to be more cost effective to use a mixture of battery and hydrogen storage rather than either one [81, 82], reflecting the lack of fast dynamic control of the present generation of fuel cells and electrolysers.

The optimal operation of the hydrogen system is also a practical consideration [76]. The inclusion of batteries helps to smooth the supply to the electrolyser, allowing more control over its operation and increased operational lifetime.

4.2.3 The Zebra battery

Due to the problems with lead-acid battery technology highlighted in section 2.5.1, a new high temperature battery technology, based on molten sodium nickel chloride, has been chosen [55]. The trade name for this unit is the 'Zebra' battery and it was supplied by Beta Research and Development, Derby, UK [83].
4.2.3.1 Battery characteristics

Sodium nickel chloride batteries appear to have a number of advantages over the lead-acid battery. These include [50]:

- **Full nameplate capacity usage**
  The full range of state of charge (100% through to 0%) can be utilised.

- **100% coulombic efficiency**
  The amp-hours going into the battery equals the amp-hours coming out. This also means the state of charge is proportional to the integral of the battery current and is directly measurable.

- **High temperature operation**
  This allows isolation from the ambient temperature so performance is unaffected by local temperature variations, which can affect the capacity and lifetime of other battery technologies.

- **High voltage series strings**
  There is no requirement for equalisation and the cells fail to short circuit, so the cells can be arranged in series strings to give high output voltages.

- **Low maintenance**
  The battery pack is totally enclosed and requires virtually no maintenance.
• Higher energy density

120 Wh/kg, approximately three times that of lead-acid batteries.

These batteries have been used in electric vehicles [55] but have not yet been used commercially for stand-alone power supplies. This could be a large potential new market for this technology.

Temperature regulation is required, so some energy is used maintaining the internal temperature. In practice, this is minimised through thermal insulation. The voltage at which the current enters or leaves the battery will differ, which will affect the overall battery electrical efficiency. They are approximately five times the cost of lead-acid batteries but have great potential for cost reduction through mass production.

It was decided to use sodium nickel chloride batteries due to their advantages over lead-acid type and the opportunity for new research into their use within stand-alone power supplies.

4.2.3.2 Battery simulations

A computer model of the system was developed, using the specifications of all the installed equipment. The model is explained in more detail in section 8.2. The results of the simulations run on this model were used to help indicate the battery capacity required.

4.2.3.3 Initial battery sizing

Running the simulation with different battery capacities and looking at the operation of the electrolyser helped to initially size the required store. All other values were held constant. Only one fuel cell was included on the system, with a maximum power rating of 2kW.

The Zebra battery cells were only available with a capacity of 32Ah. The battery capacities tested were multiples of this.

Figure 4-6 shows the reduction of electrolyser cycles with increasing battery capacity. It can be seen that even a small amount of battery capacity greatly reduces the amount of electrolyser on/off cycling.
Adding a battery bank will also affect the operation of the fuel cells and the back-up generator. Figure 4-7 shows that an increasing battery capacity would reduce the time for which both the fuel cell and back-up generator run.
Although the reduction of electrolyser cycles was the most important requirement, this must be weighed against the cost of adding more storage. It was initially decided to use a 32Ah capacity battery, as more capacity could be added later.

4.3 Final system design
A DC interconnected system has been selected as both technically attractive and meriting research and demonstration. The requirements of the electrolyser lead to the need for some form of additional short-term storage, for which a Zebra battery is used. Figure 4-8 shows the full stand-alone power system installed at West Beacon farm.

This system must supply reliable power to the domestic dwelling. For this reason, a back-up grid connection has been included in this system. One aim of the research is to show that this can be disconnected and that the system will still function satisfactorily.
Figure 4.8. The DC interconnected stand-alone power system for West Beacon Farm.

**Key:**
- SM = Synchronous Motor
- SG = Synchronous Generator
- IM = Induction Motor
- IG = Induction Generator
- PV = Photovoltaic Array
4.4 Summary

The main design of a stand-alone power system for West Beacon Farm has been presented in this chapter along with justification for the additional short-term storage requirement. The backbone of the system is a high voltage DC busbar to which the various components are connected via power electronic converters. A hydrogen energy store provides long-term storage, whilst a high temperature Zebra battery provides complementary short-term storage.
5 Power Electronics

As already described, multiple power electronic converters have been used to connect the generators and loads to a high voltage DC busbar. Using multiple small converters allows greater flexibility, redundancy and allows easy and modular connection of generators and loads. When not in use they can be shut down, reducing the standing loads and allowing more efficient system operation. In the long-term, power electronic devices are becoming cheaper, more efficient and reliable [84], so the cost of multiple converters could be offset by their advantages.

Power electronics also enables more flexible coupling with the aim of increasing renewable energy penetration into such systems.

By using power electronic converters, variable speed operation of the wind turbine can be achieved, allowing greater extraction of energy from the wind [85, 86], while reducing wear on mechanical components.

The voltage and frequency of all loads can be accurately controlled. Induction motor loads can be soft-started, reducing mechanical loads and inrush currents.

As the generator and load frequencies are not directly linked, the power quality supplied to the loads can be improved over what might be expected in small power systems [15].

5.1 Industrial motor drives

The power converters used in industrial applications, as highlighted in section 4.1.2.1, are called motor 'drives'. They are produced in high volume and are approximately one third of the price of DC to AC converters specifically built for renewable energy systems [87, 88]. For this reason, it was proposed that standard industrial motor drives be used to connect the AC generators and loads, although it is accepted that their performance and use in some applications may be inferior to bespoke designs.
5.1.1 Drive power electronics

A standard industrial drive comprises a diode bridge rectifier, a DC link with some capacitance and a three-leg IGBT inverter bridge, as shown in Figure 5-1 [72].

Induction machines require reactive power to operate. Current in the stator sets up a varying magnetic field that induces a voltage in the conductors of the rotor. The induced voltage sets up an induced rotor current that creates a counterbalancing magnetic field. The interaction of the two magnetic fields causes the rotor to turn. The reactive power required is due to the magnetising current.

There are four quadrants of AC machine operation as shown in Figure 5-2. By controlling the voltage and frequency, a motor drive can work in all four quadrants [89]. Drives can be used to supply or extract power from both induction and synchronous machines.

Figure 5-1. The motor drive.

Figure 5-2. Four-quadrant power flow.
Drives can be connected together at the DC voltage level, without using the diode rectifier, as shown in Figure 5-3. Power can be transferred through the DC busbar to and from the various drives. In addition, using inductors, a drive can be connected to a grid or a synchronous generator. The phasor diagrams for this are also shown in Figure 5-3 [72].

Figure 5-3. Back-to-back motor drives.
In an industrial application, the system would be connected to the grid through regenerative inductors and a drive (shown as ‘motor drive 1’). This would supply energy to the system and the other drives (shown here as just one drive, labelled ‘motor drive 2’, but there could be any number of drives paralleled to the DC link) would power the loads as required.

5.1.2 AC generation using pulse width modulation

Pulse width modulation (PWM) of the DC voltage is used to generate a switched version of the required AC voltage. The PWM concept is shown in Figure 5-4. To create the output PWM waveform, a reference sine wave for each phase is compared to a reference triangle wave. For simplicity, only two reference waveforms are shown here. When the sine wave is greater than the triangle wave, the output is switched on. This applies the DC bus bar voltage, with respect to the negative DC bus bar, to the output leg of the IGBT bridge. The output voltages of the three legs of the bridge combine to give the line voltage shown. As the motor is mainly an inductive device, the applied voltage will induce a current to flow. The output current will include a small ripple. In a real drive, the switching frequency would be much higher than shown.
Normally control of the output line voltage is required to control the speed of the motor, which must be achieved even with a varying DC bus voltage, within certain limits. The internal control within the drive does this by controlling the modulation value, $M_a$, which is defined as the ratio of the peak of the reference sine wave divided by the peak of the reference triangle waveform, shown in equation 5-1.

Usually the triangle waveform frequency and amplitude is constant, while the reference sine wave is varied to adjust the modulation.

$$M_a = \frac{\hat{V}_{\text{ref}}}{\hat{V}_{\text{tri}}}$$

The peak of the output voltage with reference to the negative DC bus bar is:
And the RMS line voltage is: \( V_{\text{line}} = \sqrt{3} \frac{V_{\text{outl}}}{\sqrt{2}} \)  

Combining equation (5-1) with equation (5-3) gives:

\[ V_{\text{line}} = \frac{\sqrt{3}}{2} M_a \times V_{dc} \]

So adjusting the peak of the reference sine wave can directly control the output line voltage.

### 5.1.3 Inverter drive suppliers

Control Techniques were chosen to supply the motor drives for this system. Reasons for this include:

- Well established and leading company in drive technology.
- They both manufacture drives and build drive systems.
- The drives are manufactured within the UK and hence have local technical support.
- When approached they showed an interest in the project and were forthcoming with help and support.
- Their Unidrive series of motor drives had all the features required and were available in a wide range of power ratings.

### 5.1.4 DC busbar specifications

The use of industrial motor drives affects the choice of voltage on the DC busbar. Standard 400 V AC rectified to DC is 560 V. This is the minimum voltage at which the drives will function. Their maximum working voltage is 820 V DC, therefore the voltage range of the DC busbar is between 560 and 820 V DC.

The use of a relatively high voltage permits greater transfer of power through cables of a given cross section.
5.1.5 Zebra battery voltage rating

The Zebra battery is directly connected to the DC busbar. In order to charge the battery the DC busbar voltage must be greater than the nominal open circuit voltage of the battery. Its voltage range must therefore be compatible with the bus voltage range. The battery system comprises the physical chemical cells, an outer casing with vacuum insulation and a battery management interface. The interface comprises of a microcontroller and a contactor. Depending upon various parameters monitored by the microcontroller the contactor will be operated to allow power into and out of the battery while ensure no damage occurs to the battery due to misuse. The interface has been designed for a maximum voltage of 750V DC, which is the rating of its circuit board and components. The cost of redesigning the interface was prohibitive; therefore, this was taken as the maximum battery voltage. The minimum battery voltage is 560 V DC, beneath which the drives cannot function correctly, as they are unable to reproduce a full 400V AC waveform.

The battery consists of a string of cells connected in series. Data from the manufacturer showed that the maximum allowable voltage was 3.1 V per cell, associated with a high recharging current. The maximum number of cells within the series string was therefore 750 V / 3.1 V per cell = 240 cells. The nominal cell voltage is 2.58 V per cell, making the nominal battery voltage 620V DC. The capacity of the battery is 32Ah, sized by performing system simulations.

5.2 Other DC-AC conversion

The connection of the rotating generators and loads has been discussed in section 5.1. The various domestic loads must also be supplied, as they would by the grid, with 230 V AC and 400 V AC 50 Hz waveforms. As shown on the system diagram, Figure 4-8, industrial motor drives are used to perform this function. Their output was set to a constant voltage at 50Hz. This is supplied to the loads via a switching frequency filter and a transformer. The switching frequency filter removes frequencies above approximately 100Hz, including the switching frequency, and so the output only contains the smooth 50Hz waveform. The filter was designed by the drive manufacturer. The transformer is required to provide galvanic isolation, which
will stop any DC voltage to protect the loads and the user from the DC busbar voltage in case of a possible power electronic fault.

This solution required only off the shelf components. It is not ideal, as large and heavy transformers are required, as they must work at 50Hz. In addition, there is no voltage control loop to ensure the voltage waveform is maintained.

Inverters designed for stand-alone applications, based on multi-stage high-frequency topologies, may be more appropriate [42]. Changes may be required to enable them to work from the high voltage DC busbar.

5.3 Electrolyser power supply

The electrolyser was previously connected to a three-phase AC supply and therefore includes a rectifier stage to supply DC to the stack. This was altered to connect to the DC busbar as shown in Figure 5-5.
Again, the use of an off the shelf inverter drive was the most cost-effective and simple solution, as all the equipment required to connect to an AC supply (a phase controlled thyristor stack, a transformer and a diode bridge rectifier) was already present. To be precise, the commercial drive replaces the thyristor phase controller
of the electrolyser power supply as originally supplied. It allows control over the voltage applied to the transformer. However, an additional switching frequency filter was required, as the transformer insulation was not rated for the drive direct output voltage, which has pulses equal to the DC busbar voltage.

5.4 DC-DC converters
The DC generation sources (PV arrays) and the DC loads (fuels cells) are not compatible with the DC busbar voltage [90], and hence DC-DC converters are required for their connection. Commercial converters were not available so the production of a bespoke design became a key element of the research. The design of these converters is discussed in detail in chapter 6.

5.5 Summary
Standard industrial motor drives provide a low cost and effective building block for connection of the rotating machines to the power system. Such drives are used extensively and are thus well developed and reliable. Bespoke converters are also required to interface the other components.
6 DC-DC Conversion

6.1 DC-DC converter requirements

The voltage of the main bus bar has been set between 560 and 750V DC, to which the various DC devices must be connected. The direct connection of DC generators to hydrogen storage systems has been previously investigated [90]. However, due to the large voltage differences in this instance, DC-DC converters are required.

The main DC-DC converters required are for the solar PV arrays and fuel cells, which both require step-up converters. The electrolyser stack is also a DC device but requires a step-down converter at a very high power level and, as already explained, the standard power electronics supplied with the unit have been adapted. The Zebra battery requires no conversion as it is connected directly to the DC busbar.

In order to choose the most appropriate converter topology, the general characteristics of the DC devices must be known [91].

6.1.1 Solar PV module characteristics

All the photovoltaic modules installed at the farm are crystalline silicon, although a range of different manufacturers products have been used. Such modules have a current/voltage (IV) characteristic much as shown in Figure 6-1. The current and voltage are mainly affected by changes in irradiance (W/m²) and, to a lesser extent, by other variables such as temperature.
Modules are built from a number of cells in order to supply a higher voltage and current. Modules are then connected into an array, with series and parallel connections used to give increases in voltage and current. If the panels are wired in higher voltage series strings, they will have a lower current for the same power level and hence lower resistive losses and thinner, less expensive, wires.

For maximum power transfer, the voltage and current must be maintained at the maximum power point [92, 93]. The irradiance onto the array might not be constant over the whole area, due to shading or clouds. This can change the IV characteristic and hence the maximum power point.

The installed PV panels are wired into four arrays of 1.5 kWpeak at a 120 V DC nominal voltage, as mentioned in chapter 3.3.2. These require four converters with step-up ratios of approximately seven and power ratings of 1.5 kW, to interface to the DC busbar.

### 6.1.2 Fuel cell characteristics

Both fuel cells used within this system use a proton exchange membrane (PEM). They are low-voltage, high-current devices, comprised of a number of individual cells in a stack. Hydrogen and oxygen (usually from the air) are passed through the stack.
Current is generated proportional to the surface area of the cell, the temperature and the gas flow rate [60].

The current/voltage characteristic for a typical fuel cell is shown in Figure 6-2.

![Fuel Cell Current/Voltage Characteristic](image)

**Figure 6-2. Typical IV characteristic of fuel cell [60].**

It can be seen that the output voltage varies significantly with generated power. Therefore, within the fuel cell system, a power electronic converter maintains a constant output voltage. A small integral lead-acid battery store is used to help buffer the load from the stack.

A converter with a step-up ratio of approximately 32 and power rating of 2 kW is required for the Intelligent Energy fuel cell. The Plug Power fuel cell requires a step-up ratio of approximately 16 and power rating of 5 kW.

### 6.2 Commercially available converters

Most commercially available DC-DC converters are designed either for low power applications. Of the higher power converters, most are designed for recharging lead acid batteries at 12, 24 or 48 volts. At present, there is no market for high power, high voltage step-up ratio converters as required for this system, and hence no 'off the shelf' units could be sourced. It is for this reason that a specially designed converter was developed, the design of which is presented in the rest of this chapter.
6.3 Basic DC-DC conversion theory

There are many different circuit topologies for DC-DC conversion, each with different characteristics [89, 94]. The conversion ratio, $R_c$, defined below, and the power to be transferred through the converter need to be known to select the most appropriate conversion topology for the application. In practice, there are normally a number of possible solutions. The efficiency, $\eta$, of the topology must also be taken into account.

![Figure 6-3. A basic DC-DC converter](image)

Conversion ratio: $R_c = \frac{V_{out}}{V_{in}}$

6.4 Overview of step-up topologies

The main DC-DC conversion topologies can be split into two categories. Non-isolated converters, which have a direct electrical path from input to output, and isolated converters, which have some form of isolation between input and output, usually in the form of a transformer. These are presented in this section [89].

6.4.1 Non-isolated converters

6.4.1.1 Boost

The circuit diagram for the basic boost converter is shown in Figure 6-4.
The duty cycle, $D$, of any switched circuit is the ratio of the on time, $t_{on}$, to the total period, $T$.

$$D = \frac{t_{on}}{T} \quad 6-2$$

The step-up ratio equation of the boost converter, in continuous-conduction mode, is:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 - D} \quad 6-3$$

The main characteristics of this configuration are:

- Minimum complexity
- Two operating modes: continuous and discontinuous conduction, with very different open and closed loop response
- Uses a ground referenced drive circuit
- Large current must be switched
- Used for relatively low output voltages (up to 50V) and powers (up to 50W)
- Maximum practically achievable step-up ratio of five.

It does not provide input output isolation.

### 6.4.2 Isolated converters

#### 6.4.2.1 Flyback

The basic flyback converter topology is shown in Figure 6-5.
The step-up ratio equation, in continuous-conduction mode, is:

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = n \cdot \frac{D}{1-D}
\]

In addition to isolation, the main characteristics of the flyback design are:

- Uses inductance of the transformer for operation, hence an air gap in the core is required for energy storage
- High step up ratios achievable
- Uses a ground referenced drive circuit
- Used for output powers up to 200W

### 6.4.2.2 Push Pull

The basic push-pull converter circuit diagram is shown in Figure 6-6.
The windings on the primary side are switched alternately. The step-up ratio is:

\[ \frac{V_{\text{out}}}{V_{\text{in}}} = 2 \cdot \frac{N_2}{N_1} \cdot D \]

The push pull inverter provides isolation. Its other main characteristics are:

- Duty cycle of each switch is limited to 50%
- Energy transferred in both halves of the cycle
- Isolation between input and output
- Quite efficient and compact
- Two switching devices are required
- Switching device voltage rating must be twice the input voltage
- 'ON' periods must be exactly equal or core saturation problems can occur.

This is hard to achieve in practice [89].

### 6.4.2.3 Forward converter

The basic forward converter topology is shown in Figure 6-7.
The step-up ratio equation is:

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{N_2}{N_1} \cdot D
\]

Its key characteristics are:
- Duty cycle limited to 50%
- Energy transferred only during one half-cycle
- Isolation between the input and output

### 6.4.2.4 Full bridge

The basic full bridge converter topology is shown in Figure 6-8.
A full bridge converter also provides isolation between input and output; it has the following additional characteristics:

- Maximum utilisation of the transformer core
- High step-up ratios are achievable
- Four switching devices are required
- Generally used for higher power applications
- Requires both high and low side switch drivers
- The transformer volt-seconds balance must be maintained or core saturation problems may occur. As with the push-pull topology, this is hard to achieve in practice.

### 6.5 Initial converter design

The power rating of the Intelligent Energy fuel cell and a single PV array are in the same region, at 2kW and 1.5kW respectively. With isolated inputs and outputs, power converters can be connected in series and parallel. A modular unit could be repeated to provide the required step-up ratios and power throughputs, as shown in Figure 6-9, as long as the insulation barrier is capable of the highest voltage in the system and switching device specifications are capable of the highest voltages required.
For this reason, a suitable modular unit was developed as a building block for the DC-DC converters required in the system.

### 6.5.1 Design specifications

A prototype unit was required to test the chosen converter topology. Four modular units were designed and built to ensure their correct operation. The specifications given here are only for the fuel cell converter. For the solar converter the same topology could be used but the input and output voltage specifications will be different.

The prototype unit specifications were:

- **Power output:** 500W
- **Input voltage:** 20-30V DC
- **Output voltage:** 150-200V DC
- **Max step-up ratio:** 10
- **Efficiency:** >80%
- **Maximum input current:** $\frac{500}{(20 \times 80\%)} = 31.25A$
A high switching frequency is used to reduce the size of the magnetic components. The rest of this chapter deals with the design, construction and testing of a modular converter.

6.5.2 Topology choice
As already stated, the choice of topology depends upon many factors, including power rating, cost, efficiency and ease of construction.

Due to the power throughput required and the fact that isolation must be maintained, three of the main topologies identified above could be used: forward, push-pull and bridge.

Although able to cope with the power requirements, the bridge converter topology was seen as too complicated, as it required a number of switching devices and drivers. Both the bridge and push-pull topologies are difficult to operate, as the volt-seconds applied to the transformer must be perfectly balanced to stop magnetic saturation occurring. For circuits requiring isolation and rated between 200W to 1kW, the forward topology is recommended [95].

A variant of the forward topology, the two-transistor forward converter, was chosen. This had the advantages of simple operation and control circuitry, isolated inputs and outputs and high step-up ratios. A maximum of half a duty cycle can be used to transfer energy. A larger and more expensive transformer is therefore required for the same power throughput.

6.6 Two transistor forward converter design

6.6.1 Principles of operation and waveforms
The two-transistor power circuitry is shown in Figure 6-10.
Figure 6-10. The two-transistor forward converter [89, 96].

Figure 6-11 shows the current and voltage waveforms for the circuit operation. These waveforms relate to continuous mode operation, during which the output current is always greater than zero.
Voltage is applied to the primary windings of the transformer when the two switching devices are turned on. A current, $I_{in}$, will flow. This induces a voltage on the secondary windings equal to the $n$ times the primary voltage. A current will flow through to the output inductor, while diode $D_3$ conducts. The devices are then switched off. 'Freewheeling' diodes on the input side allow the current stored in the transformer magnetising inductance to flow back to the supply. This will automatically reset the volts-second balance to the transformer, as long as the duty cycle is never greater than 50%. When the switching devices are off, the potential on the secondary side is reversed, which allows current to flow through $D_4$. The inductor will try to maintain a flow of current to the output but this will have a small ripple, the
magnitude of which is proportional to the value of the inductor. A capacitor smooths the output voltage. The output voltage will be proportional to the duty cycle, the step-up ratio of the transformer and the input voltage, shown by equation 6-8.

$$V_{out} = \frac{N_2}{N_1} \cdot D \cdot V_{in} \quad \text{6-8}$$

### 6.6.2 Converter control principles

The requirement is to transfer power from the input to the output. The voltage on either side of the converter can vary within specified operating ranges. This makes the control strategy one of controlling the current through the unit. The output current is used as the feedback control parameter [97, 98].

Figure 6-12 shows the control circuit operational waveforms. The inductor current is monitored. This signal is filtered to remove switching frequency effects and other high frequency noise. A user reference set-point controls the output current required. This is compared to the filtered inductor current. The result is compared to an internally generated saw-tooth waveform. This generates the pulse width modulated pulses to control the switching devices. Only alternate pulses are used to allow for the 50% 'blanking' time required to reset the transformer volt-seconds balance. The pulse width will increase or decrease depending upon the required current.
6.7 Converter simulation

Before any practical work was undertaken, the basic circuit was simulated using an electronic simulation package called OrCad. This used PSpice models to look at the operation of the circuit. In addition, circuit diagrams could easily be exported to a printed circuit board design package. The simulation circuit diagram is shown in Appendix 19-1.

6.7.1 Converter simulation results

The simulation results are shown in Figure 6-13.
These waveforms confirm the basic operation and shows that a 200 V DC output can be generated from a 24 V DC input. As with all simulations, there are some simplifications. Most importantly, the physical layout and construction method are not taken into account, which may affect the operation and efficiency of a realised circuit.
6.8 Full converter design and construction

The basic power and control operation has been explained and simulation results shown. The rest of this chapter deals with the physical design and component selection for the prototype. Appendix 19-2 shows the final power circuit diagram.

6.8.1 Basic magnetic theory

An understanding of magnetic theory is required to design effective transformers and inductors for operation at specific frequencies.

For a single coil of wire wrapped around a core, such as shown in Figure 6-14.

\[
N \cdot \frac{d\phi}{dt} = v
\]

Where \( v \) is the induced voltage, \( \phi \) is the magnetic flux, \( t \) is the time and \( N \) is the number of turns.

Amperes law states:

\[
\phi = \int B \, dA
\]

Where \( B \) is the flux density and \( A_e \) is the effective core area. If \( B \) is constant then this equation simplifies to:

\[
\phi = B \cdot A_e
\]
Where $A_e$ is the effective core area. Differentiating 6-11 and substituting into 6-9 gives:

$$N \cdot A_e \cdot \frac{dB}{dt} = \nu \tag{6-12}$$

The magnetic flux is related to the magnetomotive force, $F$, through the equation:

$$\phi = F = N \cdot i \frac{W}{\mathfrak{R}} \tag{6-13}$$

where $\mathfrak{R}$ is the reluctance and $i$ is the current flowing through the wire. The reluctance of a magnetic path is given by:

$$\mathfrak{R} = \frac{l}{\mu_0 \cdot \mu_r \cdot A_e} \tag{6-14}$$

$\mu_0$ is the permeability of free space ($4\pi \times 10^{-7}$), $\mu_r$ is the permeability of the material and $l$ is the effective length around the magnetic circuit.

The flux linked, $\lambda$, by $N$ turns on the core, is:

$$\lambda = \phi \cdot N \tag{6-15}$$

Substituting equation 6-13 in 6-15:

$$\lambda = i \left( \frac{N^2}{\mathfrak{R}} \right) \tag{6-16}$$

The bracketed terms in 6-16 are constant for a given coil and core, and are termed inductance, $L$.

$$L = N^2 \frac{2}{\mathfrak{R}} \tag{6-17}$$

Rearranging 6-15, differentiating and substituting in 6-9 gives:

$$\nu = \frac{d\lambda}{dt} \tag{6-18}$$

Differentiating 6-16 and substituting in 6-18 gives:
This is the standard inductor equation and is used in both transformer and inductor design.

6.8.2 Transformer design

6.8.2.1 Magnetic theory of transformers

Similar calculations can be performed for two coils mutually coupled by a core, shown in Figure 6-15.

By interpreting Maxwell's law, the total flux through the first coil, $\phi_1$, comprises the magnetising flux, $\phi_m$, and a leakage flux, $\phi_l$, because the coils will not be perfectly linked.

$$\phi_1 = \phi_m + \phi_l$$  \hspace{1cm} (6-20)

This can be re-written in terms of flux linkages by multiplying 6-20 by the number of turns and replacing with 6-16.

$$L_1 \cdot i_1 + L_m \cdot \left( i_1 + \frac{N_2}{N_1} \cdot i_2 \right)$$  \hspace{1cm} (6-21)

$L_1$ is the leakage inductance, $L_m$ is the magnetizing inductance and $N_1$ and $N_2$ are the respective number of turns on coil 1 and 2. It is useful to view two mutually coupled coils, such as a real transformer, in terms of an electrical equivalent circuit.
The leakage flux of the primary and secondary coils are modelled as inductors in series with the inputs, while the magnetising flux is modelled as an inductor in parallel with an ideal transformer. Along with the resistances of the coils of wire, this forms the basis of the equivalent circuit of a transformer, shown in Figure 6-16.

![Transformer equivalent circuit](image)

**Figure 6-16. Transformer equivalent circuit [89].**

### 6.8.2.2 Design compromises

In order to design a practical transformer there are a number of design compromises. These are discussed below.

#### 6.8.2.2.1 Maximum flux density

Any given core material has a certain flux density, $B$, and magnetic field strength, $H$, characteristic. The general form of this is shown in Figure 6-17.

![Generic graph of magnetic flux density against field strength](image)

**Figure 6-17. Generic graph of magnetic flux density against field strength [99].**

Due to the non-linear relationship between magnetic field and magnetic flux density, there is a point at which the core will saturate and the material cannot absorb a
stronger magnetic field, shown as $B_{\text{sat}}$. This limits the minimum size of a transformer core in a specific application. To avoid situation, the maximum flux density, $B_{\text{max}}$, should be limited to a value chosen from the ferrite material data sheet, usually approximately ±0.2 Tesla [100].

Using equation 6-12 and assuming a square-wave voltage is applied at a frequency, $f$, it can be shown:

$$v_p = 4 \cdot N_1 \cdot B_{\text{max}} \cdot A_e \cdot f$$  \hspace{1cm} 6-22

The applied voltage and frequency affect the number of turns on the primary, as $B_{\text{max}}$ and $A_e$ are constant for a given core.

### 6.8.2.2.2 Magnetising inductance

The magnetising current is the component of the transformer current that supplies enough magneto-motive force to overcome the magnetic reluctance of the core. This current relates to the magnetising inductance on the transformer equivalent circuit. The magnetising current must not be too large, as it reduces the current available for transfer through the transformer. A general rule is that the maximum magnetising current should be less than 5% of the primary current. The magnetising inductance, $L_m$, can be calculated using the inductor equation 6-19.

The magnetising current, $I_m$, is 5% of the input current, therefore:

$$I_m = \frac{P_{\text{in}}}{V_{\text{in}}} \cdot 0.05$$  \hspace{1cm} 6-23

Where $P_{\text{in}}$ is the input power. The time taken, $t_{\text{on}}$, is proportional to the frequency and the duty cycle of the switch. Assuming a fixed periodic waveform and substituting 6-24 into 6-19, this leads to:

$$V_{\text{in}} = L_m \frac{di_m}{dt} : I_m = \frac{V_{\text{in}}^2 \cdot t_{\text{on}}}{0.05 \cdot P_{\text{in}}}$$  \hspace{1cm} 6-24

The magnetising inductance can also be calculated from empirical core data. Usually a value of inductance per turn, $A_L$, is given.

$$L_m = N_1^2 \cdot A_L$$  \hspace{1cm} 6-25

Both 6-24 and 6-25 must be satisfied for effective operation of the transformer.
6.8.2.2.3 Physical size
An additional limitation is the size of the wires, which must fit onto the transformer bobbin. A 'rule of thumb' value for the current density, \( J \), carried by a copper wire is \( 3 \times 10^6 \text{ A/m}^2 \). If the available winding area is \( A_w \) and a space factor of \( K_s \) is allowed for inaccuracies in winding, then the equation relating winding area, number of turns and current is:

\[
A_w K_s \geq \frac{N_1 \cdot I_1}{J} + \frac{N_2 \cdot I_2}{J}
\]  

This equation must be satisfied to fit the wires onto the bobbin.

6.8.2.2.4 Maximum power available from core
An equation for the maximum power available from a core at a certain frequency is obtained from equation 6-26 and replacing voltage with the power divided by the current:

\[
P_{\text{max}} < 2 \cdot B_{\text{max}} \cdot J \cdot f \cdot A_w \cdot A_v \cdot K_s
\]  

This shows the maximum power available from a core is related to the frequency and the physical size of the core.

6.8.2.2.5 Skin depth
Skin depth, \( \delta \), is the depth from the surface to which an electromagnetic wave will travel within a conductor up to an attenuation level of 1/e of its original value. For a copper conductor, it is related to frequency of operation, \( f \), by the equation:

\[
\delta = \left( \frac{\rho}{\pi \cdot f \cdot \mu_0} \right)
\]  

Where \( \rho \) is the resistivity of copper, \( 1.72 \times 10^{-8} \text{ \Omega m} \) [101].

In the case of a current carrying conductor at high frequency, such as in a high frequency transformer, it can limit the maximum usable wire diameter and hence the current that can be carried by a single wire. The wires used should be no thicker than twice the skin depth, as the bulk of the current would only flow within the skin depth. This can be overcome through the use of thin, flat conductors, such as copper.
tape, or through the use of Litz wire, made from a number of insulated parallel-connected thin strands, as shown in Figure 6-18, to carry higher currents [102].

![Figure 6-18. Litz wire construction.](image)

### 6.8.2.3 Transformer core selection

The transformer design process is iterative. A number of parameters must be satisfied for the high frequency design of a transformer. A core is selected and the equations applied to check the cores suitability. An initial core choice can be made from the maximum power available through the core, equation 6-27.

A core with the following specifications was proposed:

- **Core type:** Ferroxcube EC70 [103]
- **Material:** 3C90 [100]
- **Core area, \(A_e\):** 279mm²
- **Total winding area, \(A_w\):** 465mm²
- **Inductance per turn, \(L_i\):** 3900nH
- **Saturation flux density, \(B_{sat}\):** 0.34T

From the initial design, the maximum input current is 31.25A. The transformer must be able to handle that current through the windings. The current density, \(J\), is taken as \(3 \times 10^6\) A/m². Allowing half the winding area for the primary, the absolute maximum current capability of the core is \((462 \times 10^6 / 2) \times 3 \times 10^6 = 697\)A. The total area of the copper used within the windings must be smaller than the winding window of the core, taking into account the fill factor, \(k_{cu}\), which, with Litz wire, is normally taken to be 0.3. Therefore the actual maximum allowable winding current is \(697A \times 0.3 = 209.1\)A. This is much greater than the design input current and the core is suitable and leads to a design with:

- **Primary turns, \(N_{pri}\):** 6
- **Primary wire:** 30 x 0.6mm diameter (Litz wire)
Secondary turns, $N_{sec}$: 130
Secondary wire: 2 x 0.6mm diameter (Litz wire)

6.8.2.4  Transformer physical construction

The leakage inductance is due to the leakage flux shown in Figure 6-15. This should be minimised as it can cause the voltage to change with loading. In order to do this, the technique of inter-winding the primary and secondary can be used. This increases the number of boundaries and hence lowers the leakage inductance. A general expression for the leakage inductance is [89]:

$$L_{leak} \approx \frac{\mu_0 \cdot N_{pri}^2 \cdot l_w \cdot b_w}{3 \cdot p^2 \cdot h_w}$$

Where $l_w$, $b_w$ and $h_w$ are the dimensions of the windings and $p$ is the number of boundaries between primary and secondary turns. The leakage inductance is inversely proportional to the square of the number of boundaries.

Isolation is required between primary and secondary. This is provided to some extent by the conductor insulation. At higher voltages, this should be greatly improved for safe operation. Additional insulation can be applied in the form of high temperature insulating tape or by using copper wire with additional separate layers of insulation [102].

Figure 6-19 shows the physical construction of a high frequency transformer, highlighting the use of inter-winding the primary and secondary windings, correct insulation and multi-stranded Litz wire.
6.8.3 Inductor design

6.8.3.1 Magnetic theory of inductors

An inductor stores energy in a magnetic field. Usually an air gap is introduced into the magnetic path. This controls the maximum value of flux density at the peak inductor current and stops the core being driven into magnetic saturation.

---

Figure 6-19. Transformer construction.

Figure 6-20. Introduction of air gap to ferrite core.
With the introduction of an air gap, the reluctance given in equation 6-14 becomes:

\[ R = \frac{I_m}{\mu_0 \cdot \mu_{\text{material}} \cdot A_e} + \frac{I_g}{\mu_0 \cdot \mu_{\text{air}} \cdot A_g} \]  

6-30

Fringing effects have been included using an approximation that the air gap area is increased by \(0.5 \times I_g\) as shown in Figure 6-20. As the permeability of air \(\mu_{\text{air}}\) is 1 and the permeability of the ferrite \(\mu_{\text{material}}\) is in the region of 1000 to 4000 [100], the first term in equation 6-30 is much smaller than the second term. Therefore:

\[ R \equiv \frac{I_g}{\mu_0 \cdot A_g} \]  

6-31

Replacing this into equation 6-17:

\[ L \equiv \frac{\mu_0 \cdot A_e \cdot N^2}{I_g} \]  

6-32

This shows that increasing the air gap will reduce the inductance. The requirement is to design the inductor with an air gap just large enough to stop the core being driven into saturation at the peak inductor current.

6.8.3.2 Inductor design

In a converter power circuit, the inductor is placed after the output rectifier to maintain the output current. When the switches are on, voltage is applied and the current will ramp up. When they switch off, a reverse potential is applied and the current will ramp down. This is shown in the circuit operation waveforms in Figure 6-11.

The rate at which the current changes is a function of the voltage applied and the inductance, according to equation 6-19. The inductance therefore affects the magnitude of the ripple on the output current, which would ideally be very low. The maximum allowable ripple on the output current is the main design parameter for the inductor.

The specifications of the required inductor are:

- The maximum RMS output current, \(I_{\text{rms,max}}\): 3.3A
- The peak output current, \(I_{\text{peak}}\): 3.9A
- The maximum ripple current, \(I_{\text{ripple}}\): 1A
Operational frequency, $f$: 30kHz
Output Voltage, $V_{out}$: 200V dc
Maximum duty cycle, $D_{max}$: 0.45
Current density in the wire, $J_d$: $5 \times 10^6$ A/m²

Using this specification, along with core manufacturer’s data, an inductor was designed. Again, the process is iterative and may need to be repeated with different core specifications.

The required inductance, from applying equation 6-19, is:

$$L = \frac{V_{out} \cdot (1 - D_{max})}{f \cdot I_{ripple}} \approx 4mH$$

6-33

The power through the inductor is, using equation 6-19:

$$P = v \cdot i = L \cdot i \cdot \frac{di}{dt}$$

6-34

The energy stored ($E_{stored}$) is the integral of power over a certain time:

$$E_{stored} = \int_{0}^{t} P \cdot dt = \int_{0}^{t} L \cdot i \cdot di$$

6-35

In this case, the energy to be stored in the inductor is:

$$E_{stored} = L \cdot I_{rms} \cdot I_{peak} = 0.058J$$

6-36

The maximum energy that can be stored in the ferrite ($E_{ferrite}$) comes from substituting 6-12 into 6-34 and then applying 6-35:

$$P = i \cdot N \cdot A_w \cdot \frac{dB}{dt}$$

6-37

$$E_{ferrite} = N \cdot A_w \cdot I_{rms} \cdot B_{max}$$

6-38

Incorporating the copper fill area, $A_{Cu}$, the copper fill factor, $k_{Cu}$ and the current density within the wire, $J_d$, where:

$$N = \frac{k_{Cu} \cdot A_w}{A_{Cu}} \quad \text{and} \quad A_{Cu} = \frac{I_{rms}}{J_d}$$

6-39

Replacing equations 6-39 into 6-38, gives:
For the prototype converter, the same core was used to build the transformers and the inductors. For this core $E_{\text{ferrite}} = 0.06\, \text{J}$, which is greater than the required value, $E_{\text{stored}} = 0.058\, \text{J}$.

The peak core flux density must be less than the saturation value:

$$B_{\text{sat}} \geq B_{\text{core max}} = B_{\text{ac}} \left( \frac{I_{\text{peak}}}{I_{\text{peak}} - I_{dc}} \right)$$

Where $B_{\text{ac}}$, the ac core flux density, is reduced until the equation holds true. $B_{\text{ac}}$ in the prototype design equals 0.05 T.

An air gap is introduced to allow the inductor to work without being driven into saturation. The size of the air gap, $I_g$, is calculated by firstly equating equations 6-11 and 6-13:

$$\phi = B \cdot A = \frac{N \cdot i}{\mathcal{R}}$$

Therefore:

$$\mathcal{R}_{\text{total}} = \frac{N \cdot I_{\text{peak}}}{B_{\text{peak}} \cdot A_g}$$

Equating equations 6-32 and 6-17:

$$L \equiv \frac{\mu_0 \cdot A_g \cdot N^2}{I_g} = \frac{N^2}{\mathcal{R}_{\text{total}}}$$

Therefore:

$$I_g \equiv \mu_0 \cdot A_g \cdot \frac{N \cdot I_{\text{peak}}}{B_{\text{peak}} \cdot A_g}$$

With the EC70 core, the required air gap is 5.92mm in total and, assuming the total air gap will be comprised of two sections (see Figure 6-21), each section requires a gap of 2.96mm, again using a fill factor, $k_{\text{cu}}$, for Litz wire, of 0.3.

This core led to a design with:

- Number of turns, $N$: 220
- Number of strands: $2 \times 0.6\, \text{mm diameter (Litz wire)}$
- Air gap, $I_g$: $2 \times 2.96\, \text{mm}$
6.8.3.3 Inductor physical construction

The inductor is a high frequency component and, as with transformer design, skin effect must be taken into account, using equation 6-28.

Due to the high voltages that can be present, the insulation of the wire used must be correctly specified. Additional insulation may be required around the windings for safety reasons [102].

![Inductor Bobbin](image)

Figure 6-21. Inductor construction.

6.8.4 Power electronic component selection

6.8.4.1 Switching devices

Power electronic switching semiconductors include the bipolar junction transistor (BJT), the metal oxide semiconductor field effect transistor (MOSFET) and the insulated gate bipolar transistor (IGBT).

<table>
<thead>
<tr>
<th>Device</th>
<th>Maximum Voltage</th>
<th>Maximum Current</th>
<th>Power Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJT</td>
<td>Medium – 1000V</td>
<td>High – 500A</td>
<td>Medium</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Medium – 1000V</td>
<td>Medium – 200A</td>
<td>Medium</td>
</tr>
</tbody>
</table>
In this design, they are required to switch the current on the primary side and must handle high currents at relatively low voltages. The BJT requires relatively complicated drive circuitry and has a negative temperature coefficient, so is liable to thermal run-away. The MOSFET was chosen for this application, as it does not suffer from these problems, is suited to the power levels, and is relatively cheap.

The peak input current is in the region of 80A. This is the minimum requirement for the MOSFET. Additional requirements include the maximum switching voltage, the 'on' resistance and the heat-transfer rate. A number of devices were tested and, even though they all had ratings that covered the specifications, not all functioned well within the circuit. The main problem was that of overheating due to the available metal contact area on the device, which meant that heat could not effectively be transferred to the heatsink. For this reason, an oversized device was chosen, the IXFN180N10, from IXYS, which has a much larger metal back plate through which heat is transferred. The basic specifications of the device are $V_{\text{max}} = 100V$, $I_{\text{Dmax}} = 180A$, $R_{\text{on}} = 8m\Omega$ [104].

MOSFETs are voltage-controlled devices. They require a gate to source voltage of greater than 10V to switch the device on. Careful attention must be given to the gate-source voltage drive circuit. High-side switching requires a drive circuit with a voltage referenced to the source lead, which could be at a high potential. The devices have a high parasitic capacitance so current is required during switch-on. This current is dependant upon the size of the parasitic capacitors and the operating frequency. For the chosen devices, a MOSFET driver capable of instantaneously supplying up to two amps was required.

### Freewheeling diodes

Two diodes are required on the primary side of the transformer. They allow a small magnetising current to flow through the transformer, while the switching devices are off. This resets the volt-seconds balance and stops the transformer 'walking' up the B-H curve into saturation. The magnetising current had been designed to be at most 5% of the input current, $31.5A \times 5\% = 1.6A$. The current carried is low but, due to the

<table>
<thead>
<tr>
<th>IGBT</th>
<th>High – 2000V</th>
<th>High – 1000A</th>
<th>High</th>
</tr>
</thead>
</table>

Table 6-1. Switching device characteristics [89].
switching frequency, they must react quickly. 'Ultra-fast' type diodes were specified. MUR420 diodes, from ON Semiconductors, with a forward current of 4A and reverse recovery time of 50ns were used [105].

6.8.4.3 Output diodes
The diodes on the secondary side of the transformer must have high voltage ratings, and fast recovery due to the switching frequency. RHRP860 diodes, from Fairchild Semiconductor, were used. They have a forward current of 8A, a maximum reverse voltage of 600V and a reverse recovery time of less than 30ns [106].

6.8.5 Heatsink design
The lifetime of all semiconductor devices is inversely proportional to their operating temperature [107]. For reliable operation and long component lifetime, it is vital to ensure adequate removal of heat from the device.

Within a switching device, there are two main losses: resistive and switching. Both will increase the temperature of the switching device. The resistive element is an $I^2R$ loss due to the current through the device and its 'on' resistance. Heat is also generated each time the device is switched, due to its IV characteristic. This loss is proportional to the switching frequency, shown in equation 6-46 [89].

$$P_{\text{loss}} = P_{\text{switching}} + P_{\text{on}} = \frac{1}{2} V_{\text{in}} \cdot I_{\text{max}} \cdot f_s \cdot (t_{\text{switchon}} + t_{\text{switchoff}}) + R_{\text{on}} \cdot I_{\text{rms}}^2 \quad \text{6-46}$$

The input current, voltage and the switching frequency are used to calculate the power dissipation requirements.

For the two transistor forward converter, the power loss is doubled, as there are two devices. The calculated maximum power loss is:

$$P_{\text{loss}} = 2 \left( \frac{1}{2} 24 \cdot 83.3 \cdot 30000 \cdot (90 \times 10^{-9} + 65 \times 10^{-9}) + 0.008 \cdot 83.3^2 \right) = 121W \quad \text{6-47}$$

The heat generated within a device must be transferred through many layers for dispersal to ambient. Figure 6-22 shows the heat transfer paths and the equations to calculate the transfer rate.
The heat transfer paths within the device can be obtained from the component data sheets. If the device must be insulated from the heatsink then an additional layer is introduced. Careful attention must be paid to the implementation of any applied insulation. Mylar insulators with a silicone heat-transfer compound or special silicone insulators can be used. The silicone heat-transfer compound must not be applied too thickly or it will add to the heat transfer resistance.

Finally, the heatsink must be correctly sized for the required power dissipation. The temperature of the junction, $T_J$, must be kept as low as possible as it will affect the component lifetime. The data sheet specifies a maximum junction temperature of 150 °C but a value of 100°C was used in the calculations to allow some headroom. Using the manufacturer’s data the thermal heat transfer rate can be calculated:

$$ R_{sa} = \left( \frac{T_j - T_a}{P_d} \right) - R_{jc} - R_{cs} = \left( \frac{100 - 20}{121} \right) - 0.21 - 0.05 = 0.40 \text{ W/°K} $$_{6-48}

For this design, a heatsink with surface to ambient transfer value, $R_{SA}$, of 0.4 W/°K was chosen.

### 6.8.6 Full control circuit diagram

The control concept proposed in section 6.6.2 had to be implemented. The resulting circuit diagram is shown in Figure 6-23.
passive components are used to adjust the offset and gain. This is critical and manufactured by LEM [108], TLP072CP operational amplifiers [109], along with some.

The output current is measured by a hall-effect current transducer, the LTS 25FP.

Figure 6.22: Full control circuit
compared with a reference level. The filter is created from a capacitor in parallel with
the feedback resistor. This is designed to remove any switching frequency effects. A
cut-in frequency of \( \omega_c = 1/RC \), equal to 360Hz, is used.

The PWM output was generated by an 'off the shelf' comparator chip, the UC3524,
manufactured by Unitrode [109]. The saw-tooth waveform is internally generated at a
frequency chosen by an external capacitor and resistor. The saw-tooth frequency
was chosen to be twice the required switching frequency but only one output pulse is
used, therefore the maximum duty cycle is 50%.

Opto-couplers are used to provide isolation between the control circuitry and the
MOSFET drivers and to supply the required voltage and current to switch on the
MOSFETs. HCPL3120, from Hewlett Packard, [110] were chosen. Additional
isolated supplies, NMH2415S, from International Power Sources, [111] were used to
provide both low and high side switching. 100k\( \Omega \) parallel resistors are used to
remove any gate charge at switch off.

Additional isolated supplies were used to provide the required dual supply voltages
for the operational amplifiers. Resistors on the outputs of the isolated supplies
guarantee a small load to ensure their correct operation. A non-isolated voltage
regulator is used to supply the current transducer.

6.8.7 PCB design

Both the power and control circuits required bespoke printed circuit boards. The
power circuit layout requires careful consideration as a number of factors can have a
large effect upon the operation of the circuit. These include:

6.8.7.1 Current paths

The PCB tracks on the primary side must be sized correctly to take the very high
currents that flow. The copper cross-sectional area must be large enough to handle
the current. Due to their resistance, the tracks should be kept as short as possible.

The track will also have associated parasitic inductance that can affect the operation
of the circuit. This should be minimised by keeping current paths short and, if
possible, close and parallel to each other [112].
6.8.7.2 High voltage effects
The tracks after the secondary side of the transformer must be correctly distanced to prevent 'flash-over', caused by high voltages arcing across the tracks.

6.8.7.3 Electro-magnetic interference
As the converter is a high frequency switched device, a large amount of associated electro-magnetic interference (EMI) will be generated. As this design is a prototype, the only provision included to block EMI is an earthed metal grill cover for each unit, which still allows heat to escape, and placing the full converter within an earthed metal cabinet. In a commercial product, a variety of passive and active filters can be used to suppress EMI.

6.8.8 Completed converter

Figure 6-24. The completed converter.
6.9 Converter testing

Four of the prototype units were tested under a variety of conditions. The Intelligent Energy fuel cell was used as an input and power was transferred to the Zebra battery. The converters were wired in parallel on the input side and in series on the output side, as shown in Figure 6-9.

A HP 54600B oscilloscope with a Tektronix AM503B current probe amplifier, a Tektronix A6303 hall-effect current probe and an Elditest GE8115 differential voltage probe were used to collect the waveforms shown.

![Output Voltage & Close-up Input Current](image)

Input Current = 38A

Figure 6-25. Close up of input current.
Figure 6-26. Waveforms of device during operation.
Figure 6-25 and Figure 6-26 show that the converter functioned correctly. The measured waveforms are similar to the theoretical. A large capacitor on the input ensures the input current is a DC level with a small associated ripple. There is approximately 1A of ripple on the output current, due to the inductor value, as expected. The voltage is stepped up from 24V to 620V, the nominal DC busbar level. The noise on the signal waveforms is due to a mixture of noise picked up by the oscilloscope probes, noise due to the switching of the converters and noise from other switching devices on the system. Switching frequency noise is inevitable with large, high frequency currents.

6.10 Conclusion
A DC-DC converter for the integration of DC generators onto a DC interconnection has been designed, built and tested. Some problems with high step-up ratio and high frequency converter designs have been highlighted along with practical implementation considerations. A prototype converter has been proven to operate for test periods of hours. Efficiency measurements have been taken and are discussed in section 10.6.3.
7 Component Control

As discussed in section 2.2, for any power system, demand must be met instantaneously. Without any storage element, the DC busbar voltage would vary directly with the loads and generation, which, at times, can fluctuate rapidly. Power quality is affected if the DC bus voltage is not held within certain limits. The control system should ensure reasonable power quality and must therefore respond rapidly, which can prove challenging. A battery has been included due to the operational limitations of the electrolyser, as discussed in section 4.2.2. The battery voltage varies with the battery current and, to a lesser extent, with the state of charge. This provides a buffer between the various components and eases the control requirements.

The use of multiple power converters sub-divides the control structure of the system as a whole into two distinct levels: system control and device control. This demarcation is shown in Figure 7-1.

![Figure 7-1. Two tiered control approach.](image)

The system-level controller manages the power flows to the controllable elements of the system to help, as far as possible, balance supply and demand. This control action does not need to be particularly fast, due to the battery buffer. System control is discussed in more detail in chapter 8.

Control within each power-electronic interface (device-level) is required to ensure that each individual device functions correctly, producing the correct current, voltage and waveform. To achieve this, the control must be very fast acting with maximum response times of the order of milliseconds.
As far as possible, device-level control problems have been overcome by using standard 'off the shelf' converters. These have internal control loops to maintain their AC voltage and frequency. Since the operation of some of the converters differed from their intended application, additional device-level control was therefore required.

This chapter explains the control philosophies for each component, along with its implementation.

7.1 Drive operational modes
A motor drive has three basic operational modes. These are:

1. **Ready**: there is power supplied to the drive; it is healthy and is ready to run; there is no AC output.
2. **Running**: an AC waveform is generated on the output lines; the drive is healthy and not overloaded.
3. **Inhibited**: the drive will not run; a parameter is out of range, there is a problem with the supply to the drive, or an error has occurred.

These modes will be referred to throughout these control descriptions.

7.2 Wind turbines

7.2.1 Wind turbine overview
The wind turbines consist of the blades, a gearbox, and an induction machine. The gearbox increases the speed of rotation to that required for efficient electricity generation. The induction machine is used as a generator, converting the rotational torque into electrical power.

The wind turbine blades have in-built mechanical control mechanisms:

- They pitch-up to prevent over-speed.
- Stall regulation limits power at high wind speeds.

There is also a brake, which is wound off to ensure fail-safe shut down if power is lost. Anemometers measure the wind speed and a speed sensor reads the rotational speed of the blades.
The induction machine requires reactive power. Previously, this was supplied by the AC supply to which it was connected. The reactive power is now supplied by the power electronic converter, while active power can flow into the DC busbar. The principles of the drive operation are shown in section 5.1. The switching frequency filter was required as the induction machine is relatively old and the winding insulation had not been specified to accept the DC voltage level. In addition, the induction machine is 20 metres in the air and close to a helicopter-landing pad so it was thought wise to try to reduce switching frequency noise in case of any interference problems.

7.2.2 Wind turbine control

The primary requirement is to extract energy from the wind resource, with the caveat to ensure the wind turbine is not subjected to damaging forces, such as over speeding. A fail-safe approach to the control philosophy was taken.

7.2.2.1 Initial control concept

The first control system investigated required the drive to be running continuously. The concept was to remove the requirement for anemometers and a speed sensor. The drive was programmed to extract generating current but not to supply any motoring current. As the drive was always running, the drive would always know the speed of rotation. The maximum frequency was set to 50Hz. If the wind tried to spin...
the turbine faster than this maximum frequency set point, any rotor torque would generate active power. This would work up to the maximum power ratings of the drive.

The problem with this stemmed from always having the drive in ‘run’ mode. Even with the motoring current set point at zero, a small current still flowed through the stator windings of the induction machine. This applied a small load onto the machine. The blades are only aerodynamically efficient above a certain speed (approximately 40Hz). At low rotational speeds, the torque produced by the blades is very low. The load stalled the blades and meant that they could never reach the speed at which they become aerodynamically efficient.

7.2.2.2 Improved control concept

The drive was set to ‘run’ only when the blades have enough speed to generate some torque. The rotational speed sensor, along with some fall-safe circuitry, was required to provide this control signal, used to switch the drive to ‘run’ mode at an appropriate speed.

In normal operation, the blades are left free to rotate. When they reach a certain speed the drive will be set to ‘run’ mode and the power devices will be switched. The drive will initially try to ‘catch’ the spinning generator. It does this by applying a reduced voltage waveform to the induction machine at a frequency higher than the maximum speed. It then ramps this frequency down until the current drawn by the machine decreases, at which point the frequency must be close to the actual rotor speed. The drive will then increase the applied voltage and move the output frequency to that of the user set point (set to 50Hz (1500rpm), as the wind turbines were designed for this frequency).

If there is no power generated for a certain amount of time, the speed will be set to a lower value and the drive will be switched off. The blades are again left to rotate freely.

The flow diagram of normal operation is shown in Figure 7-3.
Manual Start - Press Reset

Apply power to brake - wind brake off

Set drive to 'External Trip'
Shut down power
Apply Brake

Is brake wound off?

Y

Set motor frequency to 50Hz.
Set motoring current = 0%
Set generating current = 100%

Is RPM sensor OK?

N

Is RPM > ON set-point?

N

Switch ON drive.
Scan to find motor frequency

Y

Is motor generating?

N

Set 'Motor timer' = 0

Y

Increase 'Motor timer'

Is 'Motor timer' > 'Max motor time'?

N

Set motor frequency = 40Hz

Y

Increase "Shut down timer"

Is 'Shut down timer' > 'Max shut down time'?

N

Switch OFF drive.
Allow blades to coast

Figure 7-3. Wind turbine control flow diagram.
This control strategy was implemented using a mixture of hardware and software. The hardware includes control relays required to control power to the brake, a soft start contactor, a speed-sensor conversion circuit and a speed sensor fail-safe circuit.

The speed sensor was a magnetic induction type that sensed the passing of gear teeth within the gearbox. If the speed sensor were to fail the wind turbine must shut down. This was implemented through a simple comparator circuit powering a normally open control relay, shown in Appendix 19-15.

In addition, if the brake fails for any reason the wind turbine must shut down. A control relay is enabled when the brake is wound off. If this relay is not enabled, the drive, and hence the wind turbine, shut down.

Apart from the hard-wired fail-safe control circuitry, the rest of the control was implemented using the drives internal software. Control programs could easily be uploaded onto the drive via bespoke software from Control Techniques using a high level programming language called 'Drive Programming Language' (DPL) which is quite similar to BASIC. The programming code is shown in Appendix 19-3.

### 7.3 Electrolyser

The electrolyser stack current controls the production of hydrogen. The stack current is a function of the applied DC voltage, the cell resistance and the number of cells.

#### 7.3.1 Power set-point

A signal sets the hydrogen production rate and hence the power consumed. A 4-to-20mA industry-standard noise-rejecting current signal was specified by the electrolyser manufacturer. To switch the unit on, this signal must rise above a certain level for a short length of time. The unit will then switch on and run. When on, adjusting this set point changes the hydrogen production rate, and hence the power consumed. To shut the unit down, the signal must fall to below a certain level for a short length of time. The short delay before the unit switches on and off was specified by the manufacturer to avoid rapid on/off cycling. The electrolyser control interface circuitry is shown in Appendix 19-18.
Figure 5-5 shows the basic internal power circuitry of the electrolyser. The electrolyser control circuitry has not been altered. When the signal tells the electrolyser to switch on, contacts are closed. This connects the electrolyser drive to the DC busbar, initially through a pre-charge resistor to stop a high initial current flowing.

7.3.2 AC operation
When run from an AC supply, there were two control signals, ramp-up and ramp-down. These increased or decreased the AC voltage to the transformer, which, after rectification, controlled the DC voltage applied to the stack. The control circuitry measured the DC current to the stack and compared this to the required reference value. A 'dead-band' window around the reference value is used. This helps limit any resonance or hunting that may occur.

7.3.3 DC operation
When connected to the DC busbar via a drive, ramp-up and ramp-down signals are still required. The drive is set to output a constant 50Hz frequency and the control signals adjust the output voltage amplitude accordingly. This overrides the usual voltage to frequency ratio control by changing the motor voltage specification parameter within the drive.

The voltage/current characteristic of the electrolysis cell is not linear. Therefore, the drive voltage adjustment is also non-linear. At the lower end of the operational voltage range, up to 350V AC, the drive voltage will ramp up in 10V AC voltage steps. It will then ramp up and down in smaller 1V steps depending on the current required. This control affects the response rate of the electrolyser and must be fast acting.

The control flow diagram is shown in Figure 7-4. This was implemented within the software of the electrolyser drive. The programming code is shown in Appendix 19-4 and the additional hardware required is shown in Appendix 19-14. The control signals are interfaced through opto-isolators to ensure full isolation between the electrolyser control and the drive.
A drive feeds the induction motor within the compressor. This drive is connected to the DC busbar at the same time as the electrolyser drive. The drive run signal comes from a pressure level switch on the buffer tank, which includes some hysteresis.
7.4 Fuel Cell

Fuel cells are controllable generators and should run whenever there is a power deficit. Both fuel cells are interfaced through DC-DC converters, the design and fast acting control of which has been presented in chapter 6.

For each fuel cell, two main signals are required: a run signal and a power set point. The run signal will start the fuel cell. The power set point will control the power from the fuel cell through the DC-DC converter.

The fuel cells have come from different manufacturers and have different control interfaces and different internal control structures. The practicalities of interfacing the two units therefore differ.

7.4.1 Intelligent Energy fuel cell

The Intelligent Energy fuel cell requires two signals, ‘start’ and ‘stop’, and sends two signals back, ‘fault’ and ‘online’.

In order to start the unit, a signal must be applied to both the ‘start’ and ‘stop’ lines. When the unit is ready to run, a high ‘online’ signal will be returned. When this is received, the ‘start’ signal must be set low and the unit will run. If, for any reason, there is a minor problem with the fuel cell then the ‘online’ signal will go low and the ‘stop’ signal must be toggled to reset the fault. If there is a major fault then the ‘fault’ signal will go high and the fuel cell will shut down.

The control signals are interfaced via relays and opto-isolators to ensure isolation is maintained, shown in Appendix 19-19.

Figure 7-5 shows a flow diagram of the fuel cell control.
7.4.2 Plug Power fuel cell

The Plug Power fuel cell has been designed to run as an uninterruptible power supply. Only if the mains supply fails would the fuel cell be brought online. This is detected by monitoring the internal lead-acid battery voltage.

The operation of the unit must be changed to enable on-demand operation. A serial connection to a control computer is envisaged. Satisfactory operation has not yet been proven and neither the DC-DC converters nor the control interface has been installed.
7.5 Induction motor loads
The system includes a number of induction motors, directly supplied by drives. These are prime movers for the following plant at the farm:

- Heat Pump
- Reverse Osmosis pump
- Lake, fire and hangar pumps
- Wind turbine winch

A set of contacts enables the drive to run when operation of the particular plant is required.

An advantage of using a motor drive is that the speed of the motor can be accurately controlled. This allowed motor soft starting to be used on these loads, which should reduce voltage dips on the DC busbar and reduce sudden pressure changes that may occur within the pipe-work at start-up.

7.6 Single and three phase loads
The single-phase and three-phase inverters must run continuously to supply the various loads. As this system supplies a residential building, the reliable operation of these supplies is very important. In both cases, the drives must run, except under fault conditions when the loads are supplied by an automatic transfer connection to the grid.

The drives were set to run at a constant AC voltage and frequency. Hard-wired contactors ensure that the loads are automatically transferred to the grid in the event of a fault.

7.7 Battery
As already mentioned, a Zebra battery is directly connected to the DC busbar. The various controllable loads and generators on the system are used to keep the battery the voltage and state of charge within operational limits. Without this battery, control of the DC busbar voltage would be immensely difficult.
This battery was designed originally for electric vehicle use and has its own battery management interface. This comprises voltage and current measurement, a control algorithm programmed onto a micro-controller and a main contactor. The algorithm is designed to prevent damage to the battery caused by over-charging or discharging through control of the internal contactor, which will stay closed unless a fault occurs. This is in order to protect the battery from potential damage caused by the user. Faults are normally due to a parameter that is out of range compared to those programmed into the micro-controller, including over-current, over-voltage and over-temperature.

7.8 Back-up grid connection

The grid connection provides two functions: It imports energy if the system requires additional generation capacity to come on-line when the battery state of charge is low. This control can be done on a relatively slow time scale. It also ensures the instantaneous voltage of the DC busbar stays within the operational limits of the inverter drives, 560V to 750V DC. If a large load is applied and the battery voltage falls outside certain limits, additional current is imported from or exported to the grid, the control for which must react quickly.

The grid interface drive works in regenerative mode, as explained in section 5.1. The AC voltage on one side of the regenerative inductors is controlled by the drive. The other side is fixed by the grid, as shown in Figure 5-3. This allows control of the DC voltage and of the power to and from the DC busbar.

The drive has fast acting internal control. This is specifically designed to maintain the DC busbar voltage set by the user. In a normal industrial configuration, this is required, as there is no battery storage element. When a battery is connected, the control of the grid-connection drive must be changed as, if the voltage was fixed, no battery current will flow. The battery will hold the busbar voltage within a certain range, depending upon the current drawn and state of charge. With a battery connected the requirement changes to that of controlling the current, not the voltage.

As the drive is designed to work in voltage mode, an additional control loop is required to change to current control. It was not possible to break into the voltage control loop, as this was hard-wired in the drive, so additional programming was
required to alter the drive to current control. Both the voltage and current control loops are shown in Figure 7-6. A proportional and integral controller was used to provide a fast acting response to changes in the required current set point.

Figure 7-6. Current control loop for grid drive.

The control algorithm was programmed onto the drive. A flow diagram of the control loop is shown in Figure 7-7. The current import set point is sent from the overall control system to the drive via an interface. The programming code is shown in Appendix 19-5 and the control interface is shown in Appendix 19-20.
'GRID ON' signal?

Y

Read 'Import set-point' from control

N

Vdc < Low volt ON?

Y

Increase 'Internal set-point' (+ve)

N

Vdc > Low volt OFF?

Y

Decrease 'Internal set-point' (unless = 0)

N

Vdc > High volt ON?

Y

Decrease 'Internal set-point' (-ve)

N

Vdc < High volt OFF?

Y

Increase 'Internal set-point' (unless = 0)

N

'Import setpoint' > 'Internal setpoint'?

Y

'Current set-point' = 'Import set-point'

N

'Current set-point' = 'Internal set-point'

Figure 7.7. Grid connection control flow diagram.
7.9 Solar PV arrays

The solar PV arrays are to be interfaced to the DC busbar through DC-DC converters, the control of which has been discussed in chapter 6. In order to extract the maximum energy from the solar PV array the maximum power point (MPP) must be tracked, shown in Figure 6-1. This involves adjusting the load to stay at the point where the product of voltage and current is highest. The MPP will change depending upon the solar energy available, the temperature of the panel and, to a lesser extent, other factors [41].

Tracking the maximum power point is not trivial and many algorithms have been proposed [113] including:

- Perturb and observe (the most common)
- Incremental conductance
- Parasitic capacitance
- Constant voltage
- Model based algorithms

Variations in the irradiance can occur quickly, hence the MPP tracking must act reasonably fast.

It is expected that the control algorithm will be implemented within some form of microprocessor controlling the DC-DC converter. No controller presently exists to do this and, as a result, the array is operated at a fixed voltage. This is not ideal and some loss of potential generation is consequently occurring. Time was not available to design and implement a MPP tracking DC-DC converter as part of this research. It is envisaged that the modular converter design be used with correctly rated switching devices and insulation values, along with a MPP tracking algorithm programmed onto some form of microcontroller.

7.10 Hydro systems

Both the hydro systems switch on if there is water available for reasonable power generation. In the case of the lake-storage hydro system, there is also scope for deferring generation to help with system control.

Both hydro systems generate a wild AC voltage. This can easily be stepped up using a correctly specified transformer then rectified to the correct DC voltage and
integrated to the busbar. Control of the hydro turbines would not need to be changed as they already feed a DC system at 120V DC. The power conversion equipment has not been implemented as part of this project.

7.11 TOTEM

The TOTEM combined heat and power unit is an internal combustion engine connected to a synchronous generator. It generates both heat and electrical power. The control for this unit could be either heat or electricity-led.

The desired control strategy would be to run the TOTEM unit whenever both heat and electrical energy are required. This occurs when the heat pump and the fuel cells are running, when it may be better to use the TOTEM. If only heat energy is required, the TOTEM could be run for heat energy while the excess electrical power is stored for later use. If only electricity is required, then using just the fuel cells may make more sense.

The TOTEM is interfaced through a drive operating in regenerative mode, as used for the grid connection. The on/off control signal to the TOTEM will depend upon the state of charge of the batteries.

This has not been implemented as part of this project, although the required power electronic converters have been installed.

7.12 Summary

The control of the system divides naturally into two levels: overall control and device-level control. The device-level control is distributed around the system and implemented locally. Within this chapter, the device-level control for each system component has been outlined and the practical implementation has been described.
8 Overall System Control and Data Acquisition

The challenge for overall control system is to control the power flows to maintain the DC voltage on the busbar within the operational limits of the power-electronic converters.

8.1 Overall Control Strategy

The controllable elements on the system, which must operate to ensure supply matches demand, are:

- Electrolyser
- Fuel cells
- Back-up grid connection
- TOTEM
- Deferrable loads

The control system to do this must be flexible, allow for repair and maintenance of the individual devices, as far as is reasonably practical, and be as simple as possible, which ought to improve reliability [82].

It was originally conceived that there would be no large storage element on the DC busbar. In this case, fast acting control of the electrolyser and the fuel cell would be used to match supply and demand.

With the addition of a battery, instantaneous control is now not required, as it will provide short-term smoothing. The addition of a battery means that battery voltage, current or state of charge could be used as the control parameter. Current control would require the control system to react very quickly to the rapidly changing currents flowing within the system and would be very hard to implement. Using battery voltage as the control parameter would also require the control system to react quickly, as it depends upon the current, along with the state of charge.

Changes in state of charge will happen relatively slowly. A control strategy based on this parameter was implemented, as it does not need to be as fast to respond. A visualisation of the control strategy is shown in Figure 8-1. It requires switching on the electrolyser as a dump load at a high state of charge and switching on the fuel cells, TOTEM or grid, if the battery is at a low state of charge. Ideally, the battery
state of charge should be kept as high as possible, as this would provide a buffer to what could happen in the future. However, some headroom is required to take into account the response time of the electrolyser. Hysteresis is included between the switch on and off points to stop the electrolyser rapidly cycling.

![State of charge control operation](image)

As the state of charge falls, the fuel cells are brought on line. Again, hysteresis is used to stop the units cycling. If the state of charge keeps dropping, then another generator must be brought on-line. Ideally, this might be a bio-diesel generator, but in this project, a grid connection serves as a back-up supply. The TOTEM combined heat and power unit would be brought on-line when both heat and electricity are required, which, for simplicity, is not shown in Figure 8-1. Once switched on, proportional-integral controllers are used to calculate the power set points for each device from the excess available.

### 8.2 System Simulation

The complete system was modelled. Simulations were performed to underpin the design and development of the system controller and to help size some of the components.

The simulation model was built using Simulink, a very powerful, building-block simulation program that is part of the MATLAB mathematical calculation package. Simulink allows time-stepping simulations to be performed using either simulated or
real input data. Using the same input data meant that many simulations could be run using different set points, the results from which give an indication as to the effectiveness of the control strategy and the related set points.

8.2.1 Overall simulation diagram

Figure 8-2 shows a simplified diagram of the simulation model. The power flows are added at each time step and the resulting current is calculated using the battery voltage. This flows either into or out of the battery, changing its state of charge. The actual Simulink model and subcomponents are shown in Appendix 19-8 to Appendix 19-13.

The energy flows within the system have been measured and processed to generate half-hourly averages over one year, 2004. The wind and solar generation and the single phase and three phase loads data had been obtained for a previous research project [5]. This has been used as the load and generation data for the simulations.
8.2.2 Simulation models

A general overview of each component's simulation model is given here.

8.2.2.1 Battery model

As the Zebra battery has 100% coulombic efficiency (i.e. amp hours going in equals those coming out), the basis for its model is an amp-hour integrator. The state of charge is calculated from the known capacity. Measured data from the manufacturer is used to calculate the battery voltage from the current flowing and the state of charge. Heat loss from the battery is modelled as a constant power loss.

8.2.2.2 Electrolyser model

The energy required to produce a set amount of hydrogen was obtained from the electrolyser manufacturer. This is a non-linear function and is used to calculate the flow of hydrogen depending upon the incoming power level.

An overriding limit on the minimum power has been set at 8.5 kW, 25% of the electrolyser rated power. The manufacturers of the unit have specified this value due to the reduction of gas purity at low power. This means, even if the set point is lower, the unit will still run at this level, unless switched off. The maximum power of the unit is its rated power, 34 kW.

A standing load of 150 W is also included to simulate the control circuitry losses [6], but, for simplicity, temperature and pressure effects have not been included in this model.

8.2.2.3 Fuel cell model

For this system simulation, it was decided to make a model of one generic fuel cell with standard characteristics. The fuel cell model is a controllable generator. It was assumed, for simplicity, to consume hydrogen at a rate linearly proportional to the electrical output power. A figure of 1.33 kWh from 1 Nm\(^3\) of hydrogen was quoted by the suppliers.

The model includes a 200 W minimum limit on power generation. The maximum power limit was adjusted, in steps of 500 W, from 2 kW to 5 kW and a number of simulations were run.
8.2.2.4 Hydrogen gas storage model
To simulate the storage system, the total hydrogen in and out of the buffer and the main store is integrated to give the level in each tank. The level in the buffer tank, along with some hysteresis, controls a compressor. The compressor is modelled as a constant 4 kW load when run. Limits are included to highlight when the store is empty, in which case hydrogen cannot be supplied, or full, in which case all excess hydrogen is lost.

8.2.2.5 Power converter model
The fuel cells generate power at different DC voltage levels. Some form of power electronic converter is required to integrate the fuel cells into the electrical power system. The power converter model has been kept very simple including a standing load (set at 50W) and a loss proportional to the power flowing through the converter (the converter was modelled with 90% efficiency).

8.2.2.6 Grid connection model
The grid connection model comprises a simple on/off control and a power level set point. There is no minimum power level, but a limit was placed upon the maximum power import, set at 15 kW, above which no more energy could be imported. It has been assumed the electrical energy generated is perfectly transferred to the system (i.e. 100% electrical efficiency for this component).

8.2.2.7 Overall control model
The state of charge control system shown in Figure 8-1 is implemented within the overall control model. All set points are adjustable.

8.2.3 Analysis of simulations
The results from a particular system simulation are shown in Figure 8-3. The results plotted are the daily average values over one year.
In order to assess the set points of the controllable devices (the electrolyser and the fuel cell), the simulations were performed repeatedly with small adjustments to the set-points. All other aspects of the system configuration and control were kept constant.

8.2.3.1 Electrolyser set-points

The electrolyser must absorb, as far as possible, any excess power. Due to the limit placed upon the on/off cycles, reduction of this is one aim of the control strategy. The unit had already been sized and installed and so only adjustments to the state of
charge at which the electrolyser switches on and the hysteresis could be made. These were varied while all other device set points were held constant to produce the graphs shown in Figure 8-4 and Figure 8-5.

![Electrolyser Cycles with Varying On point and Hysteresis](image)

**Figure 8-4. Variation of electrolyser cycles with hysteresis and 'on' set points.** It is obviously best to have the hysteresis as large as possible in order to reduce the on/off cycling. The state of charge at which the electrolyser switches on appears to have little effect upon the number of cycles.

![Electrolyser Energy Consumption with Varying On point and Hysteresis](image)

**Figure 8-5. Variation of electrolyser energy consumption.**
Neither changing the hysteresis nor the 'on' set point greatly affects the annual energy consumption of the electrolyser. This could be expected, as, with the same generation and loading, the amount of excess energy available for conversion into hydrogen ought to be very similar. As shown above, these settings do significantly affect the cycling, which would wear down the surface of the electrolyser cell membranes and lead to a higher failure rates.

8.2.3.2 Fuel Cell set-points

The main constraint effecting the operation of the fuel cell is the number of hours the device is able to run before the stack may need to be replaced. Therefore, the percentage run time of the unit must be minimised. An additional constraint is to minimise the running of the back-up generator. In performing these simulations, the only set-points changed were those controlling the fuel cell, while the other set-points were held constant.

Figure 8-6. Generator run-times with varying fuel cell size and 'on' SOC.
Figure 8-6 shows that increasing the fuel cell size would reduce the percentage run time of both the fuel cell and the grid import. Increasing the state of charge (SOC) set point at which the fuel cell switches on appears to increase the run time of the fuel cell and decrease the run time of the grid import.

![Graph showing energy generation with varying fuel cell size and switch 'on' SOC.](image)

**Figure 8-7.** Energy generation with varying fuel cell size and switch 'on' SOC.

Figure 8-7 shows that increasing the size of the fuel cell will reduce the energy from the back-up generator, as would be expected. It is interesting to note that, even with larger fuel cells, the required back up generation does not drop to zero. This is due to large occasional loads on the system that require greater power than the fuel cell can supply.
Generators with varying Fuel Cell Size and Hysteresis

Increasing Hysteresis

Figure 8-8. Generator run times with varying fuel cell size and hysteresis.

Figure 8-8 and Figure 8-9 show that increasing the hysteresis decreases the run times of both generators and the energy generation, but not significantly. These show that the hysteresis of the fuel cell is not critical to the control system.
8.2.3.3 System electrical efficiency

The electrical efficiency of the system and the storage elements was investigated while the battery capacity and the fuel cell size were varied. Although the coulombic (amp-hour) efficiency of the battery is stated by the manufacturers as 100%, the total energy efficiency is not. This is due to the difference in potential at which the current flows into and out of the battery. The battery efficiency was calculated by expressing the energy (watt-hours) out of the battery as a percentage of the energy (watt-hours) into the battery, taking into account the initial and final state of charge. The hydrogen store efficiency was calculated from the energy into the hydrogen system, both the electrolyser and the compressor, compared to the energy delivered from the fuel cells, along with the energy embodied in the stored hydrogen. The overall efficiency was calculated from looking at the total energy into the system compared to the
energy supplied to the loads, including the energy embodied in the hydrogen store and stored in the battery.

![Simulation Electrical Efficiency Over One Year](image)

**Figure 8-10.** Electrical efficiency with changes in battery capacity. Figure 8-10 shows the electrical efficiency does not change greatly with changes in battery capacity. With a larger battery bank, more energy flows through the battery, rather than the hydrogen store. As the battery has better short-term energy efficiency than the hydrogen store, there is a slight increase in the overall system efficiency.
Figure 8-11. Electrical efficiency and annual generated energy with changes in fuel cell size.

Figure 8-11 shows that increasing the full cell size slightly reduces the overall efficiency, even though the hydrogen store efficiency is increased. With a smaller fuel cell, the grid connection is used a lot more and, as this has 100% electrical efficiency in this model, the overall efficiency is good. As the fuel cell size is increased, more energy passes through the hydrogen energy store, which has a lower electrical efficiency, and hence the overall efficiency is lower. This does not necessarily mean that we want a smaller fuel cell as enabling the system to stand-alone, reducing dependence on the grid connection, is the aim.

The electrical to electrical round trip efficiency of the hydrogen store is in the range of 20-30%. This initially seems quite low, although the energy can be stored almost indefinitely and, as shown in Figure 2-7, at this timescale, it compares favourably with most other forms of energy storage.
Figure 8-12. Sankey diagram for simulation showing energy flows.

Figure 8-12 shows a Sankey diagram for a one-year system simulation, where the battery capacity was 32 Ah and the fuel cell capacity was 5 kW. The numbers show
the annual kWh. It can be seen that the system supplies the various loads, although the energy input is a lot greater than the energy output. Reliance upon the grid connection has been minimised by using a large fuel cell.

The full system efficiency, the total electrical energy in compared to the useful energy out, including the energy embodied within the stored hydrogen, is 47%. The penetration of renewable energy into the system is 99.9%. The overall battery efficiency is good, at around 93%.

The electrical to hydrogen energy efficiency for electrolyser, which does not include any heat energy that could potentially be recovered, is 66%. The electrical energy consumed by the compressor motor accounts for approximately 24% of the losses.

The hydrogen energy to electrical efficiency for the fuel cell is around 40%, although this does not include any heat that could be recovered. Some fuel cells are designed for combined heat and power, therefore the overall efficiency of the unit could be greatly improved through heat utilisation.

It would be most efficient to consume any excess energy directly using deferrable loads, but this is not always practical and, for this initial simulation, no deferrable loads have been implemented.

8.2.4 Simulation conclusions

No particular problems with the state of charge control system were identified from the simulations. Electrolyser hysteresis is critical to limit its on-off cycling, and the fuel cell size should be as large as economically and practically feasible, to reduce any required back-up generation.

Optimising the system as a whole means balancing the requirements of all the various devices. Compromises include the increased electrolyser energy consumption with higher hysteresis, although this reduces the electrolyser on/off cycling, and the back-up energy requirement even with larger fuel cell sizes.

These results were used as a guide for component sizing and the initial control settings.
8.2.5 Limitations of simulation

Simulations were performed to obtain design figures. The model used basic power flow models and many assumptions were made regarding the operation of the individual system components. The model is fit for purpose but is not expected to be highly accurate.

Future improvements to the simulation model could include:

- Both the electrolyser and the fuel cell models could also include temperature and pressure effects. The fuel cell model could also include the non-linear hydrogen/efficiency characteristics.
- Running shorter time-step simulations with more complex models would allow investigation into more detailed voltage and current effects.
- Deferrable loads could be added to the system.
- More complicated predictive control systems could also be investigated.

The purpose of this work was to investigate practical system design issues and thus the modelling was deliberately kept simple. Results were used initially to size system components, and then to refine system control and identify areas for future improvement.

8.3 Control and data acquisition system

An easily adaptable overall control and data acquisition system was required, in view of the developmental nature of this project. For this reason, National instrument’s LabView software was chosen, running on a computer dedicated to system control and data acquisition.

LabView software has become the industry standard for control and data acquisition, including for specialised systems and is very flexible. LabView has a graphical environment for programming and generates easy to use graphical user interfaces. It integrates easily with the National Instruments range of analogue and digital input/output cards and with many other programs and connection standards.
8.3.1 Overall control system

The control computer must be interfaced to all the controllable elements: the electrolyser, fuel cells and back-up generator. Because the devices have come from different manufacturers, most of the interfaces involve bespoke circuitry. An overview of the control interfaces is shown in Figure 8-13.

The LabView program implements the state of charge control shown in Figure 8-1. The power level at which the controllable devices run is calculated by this program. The power into and out of the battery is measured each second and this value is used to adjust the device power set point.

Limits have been placed on the minimum and maximum power levels for each device. These can be adjusted within their operational ranges. Each device can also be individually controlled, which was useful for commissioning.

Figure 8-13. Simplified diagram of the system-level control.

Two interfaces are used to connect signals to the control and data acquisition computer:
8.3.1.1 CTnet Interface

All the inverter drives have an interface for networking. This interface is normally used for commissioning the drives in industrial applications and for drive-to-drive control. Parameters in any drive on the network can be read, such as for data acquisition, and written, such as for control. CTnet is based upon a bespoke 5Mbit/s serial interface from Control Techniques. It is daisy-chained to each drive and, through an interface, to the computer. CTnet cannot be read directly by LabView, so an Object Linking and Embedding for Process Control (OPC) server is used. The OPC server acts like an interpreter allowing each side to talk to the other and hence data can be passed to and from the LabView program [114]. In order to do this a configuration file must be generated and saved on the DAQ computer, which sets up the communication paths for the OPC server.

8.3.1.2 PCI DAQ card

A National Instruments PCI DAQ NI6014 card is installed on the DAQ and control computer. The card has:

- 16 analogue input channels (16 bit resolution)
- 2 analogue output channels
- 2 frequency output channels
- 8 Digital input/output channels

This allowed digital and analogue signals to be used for control and data acquisition, via bespoke interface boards.

8.3.2 History of data acquisition at West Beacon Farm

The electrical system at West Beacon farm has been evolving for over twenty years. During that time, many different generators and loads have been added or upgraded. The renewable energy system at West Beacon Farm has formed the basis for many different research projects, which have required various data acquisition systems.

The main data acquisition system used for previous research was first installed in 1994 by Duncan Child [68]. This was updated and enlarged, with more sensors and weather monitoring added, by Rupert Gammon, as part of his work on hydrogen economies [5]. This system uses energy-measuring transducers, called Klik-meters.
These send a digital pulse to the data acquisition system each time a certain amount of energy (kWh) passes the sensor. The rate of these pulses can be used to calculate the power flowing through the system. This system will continue to function in parallel with the DAQ installed for this research.

8.3.3 New data acquisition system

The installed DC interconnected electrical system required a new control and data acquisition system. Figure 8-14 shows an overview of where the data is gathered and how it is interfaced to the DAQ and control computer.
Key:
SM = Synchronous Machine
IM = Induction Motor
IG = Induction Generator
Vac = AC voltage
Vdc = DC voltage
Vdcset = DC voltage setpoint
Iac = AC Current

Figure 8.4. DAQ system overview.

CTnet Interface

OPC Server

Data Acquisition Computer

Labview Program

Saved files (.csv)

Daily data (via e-mail)

PC/DAQ Card

100%? SOC

Batteries

PV
Fuel Cell
Fuel Cell

Hydro

I.E. Fuel Cell
P.P. Fuel Cell
Turgo Hydro
Crossflow Hydro
24V DC Power

Electrical Grid
TOTEM Chp
Single Phase Loads
Three Phase Loads
Heat Pump
Reverse Osmosis Rig
Lake and Fire Pumps
Hydrogen Compressor
Electrolyser
Wind Turbine Loads
Wind Turbine Witch
Wind Turbine 1
Wind Turbine 2
Zebra Batteries
Solar PV Arrays
The analogue input channels of the DAQ PCI card are used in non-referenced single-ended mode to monitor the various analogue data signals. The data is collected at 1000Hz and stored in a buffer until it is read into the LabView program and averaged.

The CTnet interface is used to monitor the AC voltage and current and the DC voltage within each drive. This data was already measured internally to the drive, for control, and was used rather than adding numerous additional sensors.

The data transfer rate from CTnet, via the OPC server, to Labview is quite slow. In order to gather higher resolution data, high-speed data, collected every 5ms, is averaged over 1 second within the drive itself. The averaged data is then sent via CTnet to the DAQ computer, as shown in Figure 8-15.

![Figure 8-15. Data sampling rates.](image)

8.3.4 Additional DAQ circuitry

A number of additional transducers and associated circuitry was required to measure most of the analogue data.

8.3.4.1 Zebra battery measurements

The battery current, voltage and state of charge are measured by both the data acquisition and the control systems. The battery voltage is equal to the DC busbar voltage and is read from a drive via CTnet. The current is measured using a LEM LF 305-S Hall-Effect current transducer [108]. The circuit diagram details are given in Appendix 19-16.
The state of charge is monitored through the battery management interface. This outputs a pulse width modulated signal relating to the state of charge. The signal is sent on a carrier of 300Hz, with 15% pulse width equal to 0% state of charge and 85% pulse width equal to 100% state of charge. This signal is interfaced to the DAQ card through an opto-coupler, to ensure isolation, and a resistor-capacitor filter converts the incoming waveform from a pulse width modulated signal into a voltage level that will be directly proportional to the pulse width. The cut-off frequency of the filter is 10 Hz in order to give relatively fast response to changes in the signal.

8.3.4.2 24V control system power measurements
24V power is used for all the contactors and control gear within the main Control Techniques drive panel. Additional voltage and current transducers are used to monitor the 24V control system. The sensors and circuitry used are shown in Appendix 19-17.

8.3.4.3 Fuel Cell Power measurements
Only the Intelligent Energy fuel cell was operational during this project. Data from this device is collected internally to the fuel cell system.

The DC-DC converter monitors the output current for control, so this signal was also measured by the DAQ system. The output voltage is equal to the DC busbar voltage and is monitored through a drive.

8.3.5 LabView control and DAQ program overview
Figure 8-16 shows an overview of the LabView control and DAQ program. Data is read every second and can either be averaged over longer timescales or stored directly. Comma separated variable files are used, stored on the computers hard disk. The files can be e-mailed daily. The data can also be viewed to monitor the system in real time. This facility has been very useful for both commissioning and fault diagnosis.
8.3.6 Error estimation

An estimation of the data accuracy is shown in Table 8-1. The state of charge measurement has the maximum inaccuracy of just over 10% but this value does not
need high accuracy, as it is not used for energy flow or efficiency calculations. The other signals have a maximum estimated error of 6%, which suggests the data is reasonably accurate.

<table>
<thead>
<tr>
<th>Signal Source</th>
<th>Signal Type</th>
<th>Signal Resolution</th>
<th>Sense Resistor</th>
<th>Circuitry</th>
<th>ADC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTnet</td>
<td>Vac</td>
<td>±2%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>±2%</td>
</tr>
<tr>
<td>CTnet</td>
<td>Vdc</td>
<td>±2%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>±2%</td>
</tr>
<tr>
<td>CTnet</td>
<td>Iac</td>
<td>±4%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>±4%</td>
</tr>
<tr>
<td>CTnet</td>
<td>Power</td>
<td>±6%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>±6%</td>
</tr>
<tr>
<td>Battery</td>
<td>Idc</td>
<td>±0.1%</td>
<td>±0.1%</td>
<td>±2%</td>
<td>±0.1%</td>
<td>±2.6%</td>
</tr>
<tr>
<td>Battery</td>
<td>SOC</td>
<td>±5%</td>
<td>±5%</td>
<td>N/A</td>
<td>N/A</td>
<td>±10.3%</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>Idc</td>
<td>±0.7%</td>
<td>N/A</td>
<td>N/A</td>
<td>±0.1%</td>
<td>±0.8%</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>Idc-stack</td>
<td>±0.4%</td>
<td>N/A</td>
<td>±2%</td>
<td>N/A</td>
<td>±2.4%</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>Vdc-stack</td>
<td>±0.9%</td>
<td>N/A</td>
<td>±2%</td>
<td>N/A</td>
<td>±2.9%</td>
</tr>
<tr>
<td>Control</td>
<td>Vdc</td>
<td>±0.1%</td>
<td>±0.1%</td>
<td>±2%</td>
<td>±0.1%</td>
<td>±3.1%</td>
</tr>
<tr>
<td>Control</td>
<td>Idc</td>
<td>±0.5%</td>
<td>±0.1%</td>
<td>±2%</td>
<td>±0.1%</td>
<td>±2.7%</td>
</tr>
</tbody>
</table>

Table 8-1. Accuracy of measured data.

8.4 Summary

The overall system-level control strategy has been outlined in this chapter. Simulations have been performed to show how the variation of the control set points might affect the system control. The practical implementation of such control has been described, along with the installed data acquisition system.
9 Implementation and Commissioning

This thesis describes a real system, the bulk of which has now been designed, built, installed and commissioned. The overall system is easy to present on paper as a set of interconnected boxes. The physical implementation has been a lot more involved. As far as possible, the various component devices used have been ‘off the shelf’ units. One of the main challenges has been to interface successfully all the devices that have been supplied by different manufactures and with different operational strategies.

This chapter gives an outline of the system implementation, along with some practical considerations.

9.1 Main panel

The main panel comprises the bulk of the DC interconnection system, which includes the main control gear, the grid, TOTEM, single phase, three-phase, water pump, heat pump and reverse osmosis pump drives and all the DC disconnects for the other sections of the system.

This was built by the panel-building engineers at Control Techniques to an initial design by the author. The installation at West Beacon Farm was performed by staff at West Beacon Farm and the author.
9.1.1 Grid drive

The grid drive was required in order to ensure reasonable reliability of the domestic supply. It acted as a back up generator and energy sink, if required. The control of this drive was not as simple as had been originally envisaged and many changes were required, as discussed in section 7.8.

9.1.2 Other drives

The majority of the other drives within the main panel were relatively easy to commission as their control was straightforward.
Some minor changes to the main panel have been required including the installation of residual current devices for all external loads, to comply with the BS regulations [115], and the addition of an extra drive along with switching frequency filter inductors to supply a water pump within the helicopter hangar, due to the large capacitance of the long supply cable.

9.2 Wind turbine panels

Only a four-core power cable had been installed from the main panel to the wind turbines, a distance of approximately 200m. This had been used as the three phase and neutral conductors for the wind turbines grid connection. The disruption that would be caused meant it was not possible to install an additional power cable. Therefore, the installed cable was used to carry DC to the wind turbines by paralleling up the four cores into two DC cables.

This meant that there was no AC electricity supply to the wind turbine area. An additional drive was required to supply the small local loads such as contactors and lighting. A drive was also required to supply the three-phase induction motors that power the winches used to raise and lower the wind turbines.

The components required for the DC connection of the wind turbines were split to fit into three cabinets. Two were identical, each holding a drive for a wind turbine and the related switching frequency filters and control gear. The third contained the winch and load supply drives and the required local disconnects.

These panels were built by Control Techniques engineers and were designed for outdoor installation. The physical installation on site was carried out by the maintenance engineer and author. Indicator lights were installed so that the status of the wind turbine drives could be seen at the main panel, without walking to the wind turbines.
The original control strategy for the wind turbines did not work as intended, as outlined in section 7.2. Due to the changes, additional power and control circuitry was required. This included the addition of control relays for the brakes, circuitry to
convert the speed sensor signal into a digital control signal and fail safe circuitry for the speed sensor. This fail-safe circuitry will remove the enable signal from the drive if the speed sensor signal is lost for any reason. The circuitry to do this is shown in appendix 19-15. In addition, a software program to control the drive was also required and was uploaded onto the drives via CTnet.

9.3 Electrolyser power converter

The electrolyser had been supplied to directly connect to a three-phase AC grid and hence all the supplied power electronics was configured to control the incoming three-phase AC. To connect the unit to the DC interconnection system some of the electrical equipment was replaced, as shown in Figure 5-5.

Figure 9-4. Additional electrolyser power electronics.
The required drives were supplied by Control Techniques. The design and installation was performed by the author. The power electronic system had not been tried by either the manufacturer of the electrolyser or the drives, although both agreed it would work in principle. Additional control gear was required for the drive pre-charge, for when it is connected to the DC busbar. Relays interface the power signals from the electrolyser control system to the drive. Opto-isolator boards were designed and built to isolate the control signals between the two systems.

9.4 Control and DAQ system

A number of bespoke interface circuits were required. These were designed and built by the author. They consisted mainly of control relays and opto-isolators. In addition, the overall LabView control program was developed by the author. This performs operations such as data acquisition and control, along with emailing system information and error warnings, through an easy-to-use visual interface.
9.5 Zebra Battery

The Zebra battery caused some problems during the commissioning phase. Its battery management interface was originally designed for vehicle applications and, as a result, the battery management algorithm is more complex than is required in this stand-alone application. Only the manufacturers, Beta Research and Development, had access to the battery management interface software and an engineer had to be called to sort out any problem that arose. This battery interface needs redesigning if such batteries are to be used in other stand-alone systems.

9.6 DC wiring practice

Within the electrical system, there are AC voltages up to 415V and DC voltages up to 820V. An electric shock at these voltages could easily be fatal. Safety was of the utmost importance.

Working with AC is commonplace. The safety issues surrounding the use of AC at these voltages are covered in depth in electrical installation guides.

The use of high voltage DC is not as widespread. The main industries where such voltages are used are drive systems and underground train networks.

Information on the safe use of DC was harder to source. The main points raised while installing this system are covered here.

9.6.1 Characteristics of DC

DC is just that, direct current. It does not cycle through a zero point, as in the case of AC. If a DC voltage is switched while current is flowing, a long arc can form. This can cause damage to the switch, welding it shut, amongst other problems.

9.6.2 Switching DC

In order to switch DC voltages the first requirement is that the current flowing is minimised. This means stopping the device connected so that little or no power is flowing. In the case of a motor drive, the DC switch has additional contacts wired to the drive that will inhibit the drive before the main power connections are switched.
To stop an arc forming the DC voltage must be switched in a number of sections. This reduces the potential across each section and reduces the possibility of an arc forming.

![Diagram of high voltage DC switching and fusing arrangement.](image)

**Figure 9-6.** High voltage DC switching and fusing arrangement.

Any breakers used must be rated at the correct DC voltage and current. They must be of robust construction and, when switched, break the voltage in a number of places.

The use of AC contactors for DC is permitted, according to Control Techniques, although the AC current rating must be de-rated by 50%. They must also be wired to break both the positive and negative lines. A three-phase contactor can be used but it must be wired to break the line in a number of places, which means wiring the positive line through two sets of contacts, as shown in Figure 9-6.

### 9.6.3 Safety measures

All electrical system must conform to the local electrical code of practice [115]. Good wiring practice was observed throughout the installation. The DC cables were colour coded to the new EU-harmonised colours: brown is positive, grey is negative.

Neither side of the DC busbar is earthed, as specified by Control Techniques. Due to the switching of the electronic devices within the grid-connected drive, each side of the DC bus bar is alternately connected to the grid live. If either side were earthed, a fault current would flow, through a switching device in the grid-connected drive, to the earthed busbar. Having a non-earthed system brings additional complications. The DC lines are not at a controlled potential with respect to earth. If the grid-drive was not connected and one side developed an earth fault, a fault current may not
flow. A problem could arise if a second earth fault occurs, during which the battery could supply a very large current. A solution to this problem would be to isolate the grid connection through a transformer and then one DC busbar could be connected to earth.

Each DC device has DC rated fuses in both positive and negative lines. These protect the cable from excessive fault currents.

Galvanic isolation must also be provided on any AC output supplies, in this case using a transformer. This will stop a DC potential reaching the consumer supplies, which could happen in the event of a switching device failure in the drive.

Another issue is the stored energy in capacitors within the motor drives. Standard practice is to switch off the unit and leave, powered down, for ten minutes, allowing a discharge resistor to dissipate the stored energy.

9.7 DC to DC converters

The design and construction of the DC-DC converters has been covered in chapter 6. After initial attempts at circuit development encountered difficulties, a design concept was proposed by Professor Jon Clair of Nottingham University, who is highly experienced in power electronic converters. The author however carried out detailed simulation modelling before finalising the design and proceeding with the layout and construction. As with all power electronic circuits, careful consideration of the circuit board layout and heat sink design is vital due to the high currents flowing and the fast switching frequencies.
9.8 Summary

The main parts of the envisaged DC interconnection system have been installed. However, the practical implementation and commissioning did highlight areas where more work is required.
10 System Performance

Data from the installed data acquisition system has been processed and an analysis of the main results obtained is presented here. The central system elements, the wind turbines, electrolyser, fuel cells and loads, are shown to be working satisfactorily, with the system control responding dynamically to maintain supply to the loads as required. The stand-alone operation of the system is confirmed by longer-term operational data. An energy flow analysis has also been performed.

10.1 Wind turbine operation

Figure 10-1 shows the wind turbines working, with the battery, through the DC interconnection system. The battery current follows the combined power from both wind turbines, and has the cumulative effect of increasing the state of charge of the batteries.

![Wind Power Charging Zebra Battery](image)

Figure 10-1. Wind power charging batteries.
While the Figure 10-1 shows the combined wind power, it is interesting to view the power from each wind turbine separately, as shown in Figure 10-2. Although the turbines are separated by only 20 metres, their actual generated powers differ greatly. These variations are followed by the separate drives connected to each wind turbine. It is also important to note the rapid variations in wind power that the control systems must deal with. The power from the wind turbines can vary by almost the full rated power in seconds, due to fluctuations in the wind speed and turbulence. The power converter must be able to respond to follow these changes and system stability must be maintained. Within an industrial environment, for which the drives have been designed, the power flows can change rapidly and the drive control system has been designed with a fast response. The voltage on the DC busbar varies as the current into the battery varies and, as long as this is within a certain range, system stability is maintained. The loads are separated from the fluctuations in wind power through the DC busbar and buffered by the battery and hence power quality is maintained. Occasionally, in very windy conditions, the drive cannot respond rapidly enough and the drive will trip out, which can cause system stability problems, such as rapid changes of the busbar voltage. In addition, if the wind turbines trip out, less wind energy is captured which will affect the long-term energy balance.
10.2 Electrolyser operation

A surplus of incoming wind energy will increase the state of charge of the battery. At a certain state of charge, in this case 75%, the electrolyser will switch on. This is shown in Figure 10-3, where the 'on' point is highlighted by a dashed line. A delay can be seen before the electrolyser operates. This is due to the time delay installed by the manufacturers to limit rapid on/off cycling. For the majority of time the electrolyser runs at a constant level. This is the minimum power level to ensure gas purity. The electrolyser ramps up to absorb excess wind power. The compressor power is also shown. This switches on when the buffer tank reaches a certain pressure. It can be seen from the periodicity in the trace that the unit consumes more power when the stroke of the compressor is near its end as more work is done to compress the hydrogen.

![Graphs to Show Electrolyser Operation](image)

*Figure 10-3. Electrolyser and compressor operation at high state of charge.*
The electrolyser response to variations in wind power is shown more clearly in Figure 10-4. The electrolyser is slower to ramp up than it is to ramp down. This is due to the operation of the proportional integral controller within the control program. The difference between the peak wind and electrolyser levels is due to the system loads, as only the available excess power is used.

10.3 Fuel cell operation

The operation of the fuel cell and associated power converter is shown in Figure 10-5.
The current supplied to the DC busbar is constant, at approximately 2.2 A. This current is recharging the battery, shown by the increase in state of charge. The state of charge is stepped due to the resolution of the battery management interface, which supplies the state of charge signal. The DC bus voltage varies slightly. Near to the end of graph a small voltage spike can be seen, this is due to incoming wind power, but it does not affect the operation of the fuel cell.

The fuel cell has been used to supply power to the DC busbar. Unfortunately, due to time issues with the development of the DC-DC converter, the unit has only functioned for short test periods of hours, and is not in daily operation at the time of writing.

10.4 Supplying loads

Figure 10-6 shows the AC current supplied to the loads alongside the DC current from the battery during a windy period.
The three-phase loads are supplied with the required current, which varies as loads are switched. The heat pump switches on during this time and is supplied with a fairly constant current. The battery DC current is varying greatly, due to the incoming wind energy (a negative value indicates current into the battery). The change in battery current as the relatively large heat pump load is switched on can be seen. The battery is absorbing variations in the incoming power, smoothing the supply to the loads.

10.5 Stand alone operation

The main aim of this project was to show that such a system could stand-alone. Figure 10-7 and Figure 10-8 show periods of stand-alone operation, proving the system functions correctly.
During this period, wind energy was supplied to the system. The battery buffers the current, absorbing and supplying as required. The battery current shown is negative if flowing into the battery or positive if supplied from the battery. The increase in battery voltage, associated with the incoming current, can be seen. On average, the loads are greater than the incoming wind energy and so the battery state of charge gradually falls. The loads are supplied with a good power quality, decoupled from the rapidly varying current from the wind turbines.
When the battery state of charge reaches a certain set point, the electrolyser is switched on. Figure 10-8 shows the electrolyser and loads being supplied by the incoming wind power and current from the battery for a short period. Both the battery current and voltage vary with the wind power and loads over this time. In order to maintain gas purity, 25% of the rated current must be maintained while the electrolyser is running shown by the flat sections of the electrolyser current. Above this level the electrolyser current broadly matches the wind current, which shows that the electrolyser current ramps up to absorb additional power from the wind turbines. Even with rapidly changing wind generation, the loads are, again, supplied with reasonable power quality.
10.6 Energy flows and efficiencies

10.6.1 System energy flows

The electrical system has been operational for a total of 108 days, shown in Figure 10-15. During this time, data has been collected and the total energy flows have been calculated. These are shown as a Sankey diagram in Figure 10-9. The values shown are the total energy (kWh) during the operational period.

The penetration of renewable energy into this system was 25.5% over the 108-day operational period. There has been a large import of energy from the grid (the back-up generator on this system). This has been due to a number of reasons, including the fact that the wind turbines were not operational throughout the whole period, due to delays in commissioning, and that the DC-DC converters for the fuel cells, whilst their operation has been proven, were only used for short test periods. Other reasons for the high reliance upon the grid back-up are highlighted in section 10.8. It
has been proven that the system does work and that with further development the renewable energy penetration level could be increased significantly.

The loads do not currently include the single-phase inverter, although its operation has been proven. During the initial commissioning period the system as a whole was not fully reliable, the single-phase loads to the house were left connected to the previously installed 120 VDC battery-inverter system.

Some energy is consumed by the 24V control system, the wind turbine loads (which includes the contactors and anti-condensation heaters at the base of the wind turbines) and within the drives themselves (shown on the Sankey diagram as 'System Loss'). The overall system electrical efficiency (total energy in to useful energy out) is 78.8%. This includes the losses within the electrolyser and fuel cell and the embodied energy in the stored hydrogen.

The Zebra battery efficiency was 78.7%. The loss includes the energy required to keep the battery at the required temperature and the loss due to the different potential at which the current enters and leaves the battery. Because the battery is directly connected onto the DC busbar, there are no additional converter losses.

The electrolyser electrical to hydrogen energy efficiency is 58.7%. This includes the losses in the DC to AC to DC conversion and within the stack. It also includes the energy used by the compressor motor, which accounts for 8.7% of this loss. This figure does not include the energy required by the control circuitry, also supplied by the three-phase inverter. This had been measured as an approximately constant load of 150 W [6], which equates to 388.8 kWh and reduces the electrolyser electrical efficiency to 44.9%.

The fuel cell hydrogen to electrical energy efficiency was very low, at just 5.8%, although none of the considerable waste heat has been utilised. A number of test runs were performed using a dump load, which would have consumed hydrogen but with no useful electrical output and hence greatly affected the efficiency value. Also, the flow rate to the fuel cell was measured by a mass flow meter but was very low compared to the maximum measurable flow rate of the transducer, hence noise and small offsets have a large effect upon the measured value which could significantly distort these efficiency figures. More accurate fuel cell efficiency measurements were taken during a test run and the results are given in section 10.6.3.
This data does not take into account any changes in pressure and temperature, both of which are known to affect the efficiency of the fuel cell, electrolyser and battery.

### 10.6.2 Electrolyser efficiency

Figure 10-10 shows the components of the electrolyser. The energy flows in the electrolyser system are shown. The electrolyser control system has consumed a large amount of energy, 388 kWh, as it runs constantly, which increased the electrical to hydrogen energy efficiency of the electrolyser by 23.6%. Each conversion stage has an associated efficiency. Additional energy is required to compress the hydrogen for storage.

The electrical efficiency of the power electronics within the electrolyser (the $V_{DC}$ to $V_{ACelec}$ to $V_{DCstack}$ stage) varies from 65% to 85%, shown in Figure 10-11. The electrical efficiency is lower at lower stack powers due to the proportionally higher...
constant loads. The power required for the control circuitry is a continuous standing load and varies between 100W and 200W.

Figure 10-11. Graph of electrolyser DC-AC-DC electrical efficiency at various power levels. This does not include the energy for the compressor or control circuitry.

10.6.3 Fuel cell efficiency

Figure 10-12 shows the various components of the fuel cell system. Each conversion stage has an associated efficiency.
Figure 10-12. Block diagram of fuel cell system.

Figure 10-13 shows the power levels during a few hours operation. The hydrogen power is calculated from the hydrogen flow rate multiplied by the higher heating value of hydrogen (3.24 kWh/Nm$^3$). The power produced by the stack, the power after the internal power converter and the power output of the prototype DC-DC converter are shown.
This data was sorted into output power level 'bins' and used to create average efficiency values for each stage of the fuel cell system, shown in Figure 10-14.
Although the results shown in this graph are not very conclusive, it can be seen that the overall efficiency starts low, rises through the mid-range power levels and then drops down slightly at high power. The stack efficiency is in the region of 40 to 60%. The temperature of the stack will affect the efficiency but no attempt has been made here to quantify this, as no temperature data was measured. Some of the 'lost' energy is captured as heat, as this is a combined heat and power unit, but this has not been measured. The converter within the fuel cell is between 80 and 90% efficient. This is a commercial, professionally built unit and this level of efficiency is expected. The prototype DC-DC converter has an efficiency of between 60 and 70%. This is not as good as had been hoped for at the design stage. If the prototype converters were rebuilt, a number of problems would need to be addressed. The layout of the components and the thickness of the PCB tracks would need to be redesigned to keep high current paths short and reduce heating effects due to the high current. The layout affects parasitic inductance and capacitance, which affects the operation and efficiency of the converter and this needs to be addressed. The transformer and inductor were both constructed by hand, inaccuracies in which may reduce the useful flux linkage in the transformer and the stored energy in the inductor. Faster MOSFET switching and diode operation could reduce the switching losses within the semiconductor devices. The control circuitry also needs to be
redesigned with better noise rejection, due to the amount of electromagnetic radiation, and with more accurate timed switching, as slight variations in switching may affect the operation of all four connected units. These changes could not be performed on the prototype converters, as they would require a total redesign and rebuild, and it was thought best to learn from the prototype converter operation.

10.7 Full operational data

Figure 10-15 shows the times during which the system was fully operational and during which data was collected; in total for a period of 108 days, demonstrating a promising degree of robustness and reliability at this early stage.

This grey sections of the graph show the times during which useful data was recorded. A number of periods occurred where no data was taken or the system was not functioning, which was due to complications throughout the commissioning phase of the project.

10.8 Back-up supply

The back-up grid connection has supplied the bulk of the energy to keep the system operational during the commissioning phase. This is not ideal, as this should be supplied by the fuel cells, but their long-term operation has not yet been proven.
Power is imported from the grid to recharge the battery when the state of charge is low. Figure 10-16 shows the recharge operation. It can be seen that, over a period of a few hours, the battery is recharged and its state of charge rises. The battery then discharges at a rate proportional to the applied load.

![Figure 10-16. Graph of battery recharge from grid while supplying loads.](image)

The back-up grid connection was also installed so that power could be imported or exported instantaneously to maintain the DC busbar voltage. This operation is shown in Figure 10-17. It can be seen that the battery can supply loads up to 10 kW, but since some loads are larger, energy is at times imported from the grid to meet these. The darker areas highlight the grid import.
Three factors influence the requirement to instantaneously source or sink energy:

- Electrolyser size

The electrolyser had been sized to absorb wind power while connected to an AC grid. The minimum power at which the unit can run is constrained by the design to be 25% of its rated power. It can be seen that for the majority of time the electrolyser is running at its lowest power level. Choosing a smaller electrolyser would reduce this power level and thus reduce the need to import additional power.

- Battery capacity

When a load is applied to the battery, the voltage will drop due to the internal resistance of the cells. At a certain loading, the voltage will drop below that required for correct operation of the motor drives. In this prototype system, a single battery has been installed. It can supply up to 18 A (equivalent to 10 kW) before the voltage drops below the 560V DC required by the power converters. The battery voltage will drop when the electrolyser runs if there is not enough supply from the wind. The addition of extra battery capacity could help to alleviate this problem.
• Battery connection

The grid connection is also required if the Zebra battery disconnects, which could occur for a number of reasons, including when a high current flows, due to large gust of wind, or if the battery overheats. System stability must be maintained and the loads supplied. In this case, the grid connection ought to import power to supply the loads and, if there is renewable energy generation, export any excess.

The grid drive effectively works as a current controller. If the voltage is above a certain value (680V DC) excess current is exported or, if there is a deficit and the voltage drops below a certain value (580V DC), current is imported. This operational strategy is not stable if the storage element is removed as there is no battery buffer and the voltage stays at either the high or the low value. With rapid variations, either in wind generation or demand, the drive cannot respond quickly enough and will trip out.

In addition, the grid connection has been sized to cover the loads, with a maximum rating of 37kW, and is not large enough to cover the full generation capacity of the wind turbines. Under high wind conditions, the rapid current fluctuations and the amount of generated power mean that the grid connection drive will trip out.

A battery disconnect during a windy period is shown in Figure 10-18. It can be seen that the voltage is relatively stable while the battery is connected, even with wind power generation. When the battery disconnects, the voltage drops rapidly down to the level at which the grid drive will import current (in this case 580V DC). The DC busbar voltage stays at this level until a small amount of wind power rapidly pushes the voltage up. This shows that the system is more unstable when the battery buffer is not connected. With greater amounts of wind power the voltage is pushed to the upper limit and the wind turbine drives will trip out.
A solution to this problem would be for the drive to switch rapidly to voltage control mode if the battery is disconnected. The drive would then try to maintain the DC bus voltage and the system would not vary between the import and export levels, although this has not yet been implemented. The installation of a larger drive would allow the full capacity of the wind turbines to be exported, to ensure continuous renewable energy capture.

### 10.9 Comparison of results with simulations

Table 10-1 shows a comparison of results from the simulation modelling against the measured values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full system electrical efficiency</td>
<td>47.4%</td>
<td>78.8%</td>
</tr>
<tr>
<td><strong>Renewable energy penetration</strong></td>
<td>99.9%</td>
<td>25.5%</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td><strong>Zebra battery electrical efficiency</strong></td>
<td>93%</td>
<td>78.7%</td>
</tr>
<tr>
<td><strong>Electrolyser electrical to hydrogen energy efficiency</strong></td>
<td>66%</td>
<td>44.9%</td>
</tr>
<tr>
<td><strong>Compressor energy use (as percentage of electrolyser electrical to hydrogen efficiency)</strong></td>
<td>24%</td>
<td>8.7%</td>
</tr>
<tr>
<td><strong>Fuel cell hydrogen to electrical energy efficiency</strong></td>
<td>40%</td>
<td>5.5% (system) 30-40% (test)</td>
</tr>
</tbody>
</table>

Table 10-1. Comparison of real data with simulation results.

The full system electrical efficiency is much higher for the real system due to the use of the grid as back-up, which is much more efficient than using the hydrogen energy store. This is not desirable as the aim of this project is to show that the system could stand-alone with no grid connection. The renewable energy penetration into the system is much lower for the real system. This has been due, in part, to the fact this data has been taken from the developmental stages of this project.

The Zebra battery electrical efficiencies are similar to those predicted by the model. With more data a more accurate battery model could be developed.

The electrolyser electrical to hydrogen efficiencies are also similar to the model, although the simplistic simulation model has over estimated the efficiency to some extent. Differences are most probably due to the additional energy consumed by the control circuitry and due to the three-stage (DC-AC-DC) power electronic conversion within the real system. The percentage of the losses accountable to the compressor is lower in the real system as the model used a steady power consumption value, whereas in reality the power consumption is variable and only reaches its peak at the end of each compression stroke, as discussed in section 10.2.

As explained in section 10.6.1, the measured fuel cell hydrogen to electrical energy efficiency value from the 108-day period (the 'system' value) is not indicative of the real value. The short-term 'test' value is between 30 and 40%, very close to that predicted by the simulation model.
It can be seen that there are some large discrepancies between the measured values and the simulation. The main reason for this is that the measured data has been taken from a period throughout which there has been developmental work being carried out. A number of components have not been operational and some problems with the sizing of the batteries and electrolyser have been highlighted. This has lead to heavy reliance upon the grid, although successful stand-alone operation had been demonstrated.

Long-term data is being collected with a view to creating models that are more accurate and thus increasing the accuracy of the simulations.

10.10 Conclusion

The operation of a DC interconnected stand-alone power supply system has been proven. The various system loads have been supplied with sufficient power quality. The wind turbines have been shown to work as stand-alone units. The electrolyser can convert excess energy into hydrogen and a fuel cell can convert it back into electrical energy.

The prototype system has functioned for a number of weeks. The operation over this time has been analysed and the overall electrical efficiency is in the region of 78%.

More data is required to draw any detailed conclusions regarding the long-term operation and efficiency of the system.
11 Practical Considerations
Throughout the design, construction, commissioning and operational phases of this project, a number of practical considerations have been raised. Both general issues, relating to DC interconnected systems, and specific issues, relating to the project at West Beacon Farm, are described in the following chapter. A basic economic analysis of the project is also given here.

11.1 System operation

11.1.1 West Beacon Farm system operation
The system installed at West Beacon Farm has functioned correctly for relatively long periods of days to weeks. Wind energy has been utilised either directly, or converted into hydrogen for later conversion into electricity to supply the system. The various loads have been supplied with power of sufficient quality.

The system electrical efficiency as a whole is in the region of 78%, although this is not indicative of a long-term stand-alone value that could be expected, due to heavy reliance upon a back-up connection (in this case the grid). System electrical efficiency could be improved by utilising the heat from the fuel cells and electrolyser and increased energy efficiency.

The electrical efficiency of the Zebra battery is in the region of 80%. Energy is required to keep the battery warm, which could be reduced, and hence efficiency improved, by increasing the battery insulation. Additional energy is lost due to the difference between the voltage at which the current enters the battery and that at which it leaves. This is worse at high current levels so increasing the size of the battery capacity could help reduce this loss.

The electrical to electrical efficiency of the hydrogen energy storage system is in the region of 18%, using an electrolyser efficiency of 44.6% and a fuel cell efficiency of 40%. This storage efficiency cannot be accurately calculated due to the limited operational period of the fuel cells, but it ought to be similar over longer timescales. This efficiency could be improved through a rationalisation of the power electronic converters used within the electrolyser and fuel cell systems.
There have been a number of reliability issues with this system, highlighted by the periods shown in Figure 10-15 when the system was not fully operational. This has been compounded by the fact that this system supplies a domestic residence for which any power disruption was unacceptable.

One of the main problems has been due to the inter-reliance of the various devices that comprise, what is in actuality, a very complex system. If one component fails for any reason then the system can become unstable. This is due to the high variability of the loads and the main sources of generation and the lack of any significant aggregation due to the limited scale of the system. The generators are relatively large when compared to the normal load. If a system-balancing component, such as the electrolyser, is removed and the wind turbines are generating then there is nowhere for the relatively large amounts of energy to go. Either the busbar voltage rises, or the battery state of charge rapidly reaches 100%, and the system becomes unstable.

If the grid drive fails then any additional power required cannot be supplied. The voltage of the DC connection will drop, causing the connected devices to shut down.

The fuel cells have only been run for short periods. This has been due to problems with the implementation of the DC-DC converters, rather than the fuel cells.

The main issue causing system failure has been with the Zebra battery. This component is critical to system operation, without which there is no fast acting system-balancing component. Due to problems in the software of the installed battery management interface, frequent disconnection of the battery occurred and this was the main cause of system malfunction.

The battery management interface within the Zebra battery has caused other operational problems too. The state of charge is calculated by measuring the battery current. This is integrated over time and displayed as a percentage of the rated amp-hour capacity. The current is sampled at a high frequency but small inaccuracies will add up over time, causing the calculated state of charge to move in relation to the real state of charge. For this reason, the manufacturers advise taking the battery to its full state of charge every week, which involves recharging the battery until a certain internal resistance is seen. This is calculated using the measured voltage and current, the number of cells and the cell open circuit voltage. The battery
management interface will then reset the state of charge. Figure 11-1 shows this reset happening, after which the electrolyser switches on to reduce the battery state of charge to allow some headroom.

![Figure 11-1. Graph to show battery controller state of charge reset.](image)

The inaccuracy in state of charge measurement can become quite large over time, with Figure 11-1 showing a 40% difference. This causes problems as this parameter is used to make system control decisions.

As mentioned in section 10.8, the sizing of the battery (too small) and the electrolyser (too large) have both caused problems with the stand-alone operation of this system and as a consequence additional energy has been imported from the grid.

### 11.1.2 General system operation

The operation of a DC interconnected stand-alone power system has been proven. More work is required before such an interconnection method can be said to be a viable competitor to a 'standard' AC connection, although the approach is definitely promising.
The use of a drive to achieve stand-alone operation of the induction machine-based wind turbines has worked well. In addition, induction motor loads on such a system can be easily integrated and their reliable and efficient operation can be achieved through accurate control of the voltage and frequency as demonstrated, for example, with the gas compressor. High quality AC is also available through the inverters to supply other loads.

The main general operational issues raised by the research are:

11.1.2.1 Reliability and Complexity
A power supply system for a remote community must be reliable as there will be no grid ‘safety-net’. The system proposed here relies upon a number of power electronic converters and other components from a number of different manufacturers. Each of these devices has been built with a different requirement in mind. The system is therefore very complex, and this has resulted in lower reliability than would be desirable. Much of this relates to the overall system control and a more commercial approach to this should yield acceptable reliability.

11.1.2.2 Additional storage requirement
The system presented here relies upon a battery as a short-term energy storage element. The battery was required due to the operational requirements of the electrolyser and its limited ability to track changes in generation availability. The use of a battery within a stand-alone system is not optimal, due to the additional complexity, operational requirements and cost. Their use in such systems ought to be reduced if possible and, if they are still needed, then the control of the battery must be fit for purpose. Regrettably, the battery management system supplied with the Zebra unit was not well suited to operation in the system and does need to be revised.

11.1.2.3 Energy efficiency
The overall efficiency of a stand-alone power system is a difficult concept to quantify. If loads are supplied throughout the year, does the electrical efficiency matter? The main reason it does is the high capital cost of the renewable energy generation, the
hydrogen storage system and the interconnecting components. Increasing electrical efficiency at each stage will help to reduce the capital cost.

There is scope for the system efficiency to be increased for four main areas:

- **Interconnection system**

  The DC interconnection system, including the various drives, has a number of areas where energy efficiency measures can be implemented. The drives themselves consume 4.5% of the energy flowing through the system for the test period (shown as ‘system loss’ in Figure 10-9). This could be improved by reducing the switching frequencies, although this may reduce power quality, or allowing the drives to shut down when not in use, rather than stay in ‘ready’ mode. Another area to investigate is the energy consumed by the various control contactors (‘24V loads’ and ‘WT loads’ in Figure 10-9), which totalled 6.1% of the total output energy. This could be simplified and designed with a view to reducing energy consumption, rather than for ease of connection as originally intended. Finally, the control system is implemented on a desktop computer that must be left switched on all the time. This was useful for system development, but not particularly energy efficient and could certainly be improved, perhaps through a dedicated low power microcontroller.

- **Storage system**

  There are two main storage systems: the Zebra battery and the hydrogen store. The Zebra battery was, at approximately 80%, relatively efficient for short timescales. The hydrogen storage system is less efficient due to the number of conversion stages, although energy can be stored for an indefinite length of time. The main areas for improvement are the parasitic load of the electrolyser controller and the multiple stages of power conversion within the fuel cell.

- **Loads**

  The loads are mainly domestic and the occupiers are environmentally aware, hence some energy efficiency measures are in place. The main load is the heat pump, which could be upgraded with a unit with a better coefficient of performance (which would be costly) or the house could be better insulated to reduce the heat pump run time (which would probably be the most economic way to reduce energy.
consumption). In addition, the heat from the fuel cell could be utilised, which would reduce the energy consumption of the heat pump.

- Generators

The various renewable energy generators are relatively old and could probably be upgraded with slightly more efficient new devices. The cost, including the installation costs, must be weighed against any benefit in additional energy generation.

11.2 Economic analysis

A breakdown of the main system components required to build a stand-alone power system and their costs is given in Table 11-1. The renewable energy generators had been previously installed and their cost is from the time of their installation. This has been a developmental project requiring bespoke and non-standard components, some of which have been expensive.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (£'000)</th>
<th>Percentage cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbines</td>
<td>50</td>
<td>5.2%</td>
</tr>
<tr>
<td>Solar PV</td>
<td>60</td>
<td>6.2%</td>
</tr>
<tr>
<td>Hydro turbines</td>
<td>67</td>
<td>7.0%</td>
</tr>
<tr>
<td>TOTEM CHP unit</td>
<td>5</td>
<td>0.5%</td>
</tr>
<tr>
<td>Hydrogen storage system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyser</td>
<td>140</td>
<td>14.5%</td>
</tr>
<tr>
<td>Hydrogen store (rental at £4k per quarter)</td>
<td>50</td>
<td>5.2%</td>
</tr>
<tr>
<td>Pipe work (including compressor)</td>
<td>70</td>
<td>7.3%</td>
</tr>
<tr>
<td>Fuel cells (one unit rental for 2yrs, one unit bought)</td>
<td>50</td>
<td>5.2%</td>
</tr>
<tr>
<td>Building</td>
<td>260</td>
<td>27.0%</td>
</tr>
<tr>
<td>Electrical interconnection system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverter drives</td>
<td>60</td>
<td>6.2%</td>
</tr>
<tr>
<td>DC connection equipment</td>
<td>90</td>
<td>9.3%</td>
</tr>
<tr>
<td>DC-DC converters* 7 x 2kW units</td>
<td>35</td>
<td>3.6%</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>----</td>
<td>------</td>
</tr>
<tr>
<td>Zebra battery</td>
<td>18</td>
<td>1.9%</td>
</tr>
<tr>
<td>DAQ and control system</td>
<td>5</td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>960</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 11-1. Project costs.

11.2.1 Comparison with current stand-alone solutions

At present, the majority of stand-alone power systems in use around the world are based upon diesel generators. Due to their mass production and standardisation, they are very low cost, in the region of £200 to £500 per kW [116]. The total cost of the diesel fuel and its transportation varies greatly depending upon the location and is a major factor in any economic comparison, as this cost is likely to rise in the future.

A system based upon a 30kW diesel generator supplying an average load of 2.5kW for twenty years would have a capital cost in the region of £15,000 to £20,000 and fuel costs of approximately £40,000 at £1 per litre [64] assuming no price increases. Obviously, this is much lower than the total system cost of this project, at approximately £960,000, although it is important to note the likely rise in diesel fuel cost and the considerable room for cost reduction. Other factors to take into account are environmental benefits of reducing diesel consumption and the maintenance requirements, although the maintenance may be similar with both systems due to the complexity. The building is a large percentage of the system cost and this could be greatly reduced if an existing or more basic building was used.

11.2.2 Comparison with AC system

The DC electrical integration components constituted 19% of the overall costs and specialist DC connection equipment, such as 750V DC rated breakers and contactors, were required. Within the electrical integration components, the cost of this equipment is proportionally high. The cost of the DC-DC converters is relatively high as these units were bespoke units.
An AC interconnection system, as presented in section 4.1.1, would still require the majority of the system components required for this DC system, with differences including:

- The solar and fuel cell converters would be DC to AC inverters, although with similar costs to the converters presented here.
- The electrolyser was supplied ready to connect to an AC grid and would require no additional converter.
- Some of the AC loads would require power electronics to perform a soft-start, such as the heat pump, so a number of drives may still be required.
- The hydro system was supplied to connect to a 120V DC battery bank and would therefore require some additional power conversion.
- The AC system would not require the Zebra battery, the majority of the drives nor the DC interconnection equipment.
- Some form of additional dump load or flywheel storage may also be required.

AC equipment is standard and, although a similar amount of equipment is required, it is estimated, at present, a similar system based upon an AC interconnection would be less expensive. However, such a system may have power quality problems, and some form of fast acting storage or back-up generation is likely to be required.

11.2.3 Comparison of storage systems

Table 11-2 shows a comparison between the two storage technologies used and the lead acid battery, which is typically used for energy storage at present. The cost of a 4.5 MWh storage system, the same size to that installed at West Beacon Farm, is given for comparison. The incremental cost of adding additional storage capacity is also given. This is lower in the case of the hydrogen system, as the bulk of the system is installed and only additional gas tanks must be purchased. These figures are approximate and based upon the system costs for this developmental project, so are likely to be higher than longer-term predictions.
### Table 11-2. Storage cost comparison.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Approximate system cost (£/kWh)</th>
<th>Capital cost for 4.5MWh storage (£)</th>
<th>Incremental storage capacity cost (£/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid battery</td>
<td>40</td>
<td>180000</td>
<td>40</td>
</tr>
<tr>
<td>Zebra battery</td>
<td>900</td>
<td>4050000</td>
<td>900</td>
</tr>
<tr>
<td>Hydrogen storage system</td>
<td>70</td>
<td>315000</td>
<td>11</td>
</tr>
</tbody>
</table>

It is difficult to make comparisons of storage technologies, the main problem being that the storage time is not taken into account, as discussed in section 2.2.3. Even though a lead-acid battery bank may have a lower capital cost for the same size store as a hydrogen system, it would suffer from self-discharge and would not be able to store energy inter-seasonally.

Due to the low incremental cost of hydrogen storage systems, a hydrogen store becomes more economic than using lead-acid batteries at a certain size, which ought to decrease as the technology is developed.

The Zebra battery figure is very high, as the unit was specially commissioned and cost approximately twice that of a standard 'off the shelf' Zebra battery. There is significant room for cost reduction with the Zebra battery technology.

#### 11.2.4 Summary of economic analysis

This is a developmental system and, to a certain extent, the cost of the equipment has been a less critical factor. When compared to a fossil fuel based system it is not economic, but in the long-term, it is highly probable that this will change. Now the system has been installed, the main areas for cost reduction can be investigated, including:

- Electrolysers
- Fuel cells
- DC-DC step-up converters
- DC contactors and breakers
- Battery technology
It is expected that, with mass production and standardisation, there is great potential for cost reduction within these areas.

11.3 Lessons learned

11.3.1 DC interconnected systems
Operational experience with a DC interconnected renewable energy system has been gained and information has been gathered on the systems operation and performance. Over time, it is hoped this system will be built upon and made more efficient along with the implementation of improved control algorithms.

The use of a DC interconnection has been shown to be viable for a stand-alone power system. At present, it is not an ideal solution due to the complexity and the number of bespoke devices required. With more research and development, this should change.

The use of power electronic drives is a good solution to a number of problems. Motor drives are a relatively mature technology and are flexible enough to be used in various applications. Their use for operation of wind turbines has been shown to be a viable and feasible solution.

The practical implementation of a control system is not quite as straightforward as it may first seem. Standardisation and increased inter-compatibility between the components is required. The manufacturers of hydrogen-based storage equipment and other renewable energy equipment need to work towards a common standard if such systems are to be used.

A number of components, such as the fuel cells, were the only units available at the time. If this system were to be repeated, then the specifications of the system components should be more closely tailored to the requirements of the system.

Overall, more work is required before such a system could be installed in a remote community.

11.3.2 West Beacon Farm system
A number of lessons and practical skills have been learnt, including:

- Working with motor drives, including their operation and programming
• LabView control and data acquisition implementation
• Practical issues of high frequency power conversion
• High voltage DC wiring practice

This system was installed at a private domestic location and the residents have had to live with the system. This has been far from ideal, although a number of issues have arisen from this situation including reliability of supply for real domestic loads and system safety.

11.4 Further work

11.4.1 DC interconnected systems

A number of general areas on which further research could be focussed are highlighted in this section.

11.4.1.1 Electrolyser development

The development of a more suitable electrolyser for use with renewable energy has been the conclusion of this and other research carried out on the West Beacon Farm system.

The main requirements are for an electrolyser that has:
• Fast transient response
• No problems with on/off cycling
• Wide power range
• Low parasitic loads

The requirement of additional storage could be reduced, or even removed, if the operational characteristics of the electrolyser were improved.

Using data from system such as this, a tool for the more optimal sizing of the electrolyser could be developed.

11.4.1.2 DC-DC converters

High step-up ratio DC-DC converters are required in order to interface the fuel cells. Power converters and lead acid battery storage elements are already used in the majority of fuel cell systems, which could be replaced by a single converter. There
could be a potentially large market for a reliable and efficient commercially manufactured unit.

11.4.1.3 Battery technology
The long-term performance of the Zebra battery will be monitored to ensure that such technology is suitable for stand-alone systems.

The development of this type of battery for stand-alone applications requires further work, including a specific battery controller designed for such systems.

11.4.1.4 Deferrable loads
The use of deferrable loads would help system control. The electrical efficiency of the system may be improved, as well as relaxing the requirements upon the storage elements.

11.4.1.5 Energy efficiency
If such a system were to be implemented again, efforts must be taken to ensure better system efficiency. Within the DC interconnection system, the main areas to improve energy efficiency include:

- The parasitic load of the control and DAQ computer, approximately 100W.
- Parasitic loads within the electrolyser
- Parasitic loads of the inverter drives when not running.
- Energy required maintaining battery temperature.
- Energy efficiency of the electrolyser power conversion system.
- Removal of the two-stage power-conversion system within the fuel cells.

As with any power supply system the energy efficiency of the loads must also be taken into account and improved, if possible.

11.4.1.6 Control systems
A rationalisation of the control interfaces required for each component should be performed to enable standardisation and ease of integration.

The separation of control systems into two separate levels has proved quite successful although the overall system-level control could be improved. The installed
system uses a developmental program on a computer, with associated reliability issues (such as crashing). If this type of system were to be repeated then a more robust controller would be required, with additional fail-safe mechanisms and an automatic reset if a problem occurs.

11.4.1.7 Power supplies
The use of inverter drives to supply the single and three-phase AC power is not ideal. Large, heavy and expensive 50Hz components are required along with large smoothing components. Further work includes developing inverters that are more efficient and cost-effective for direct connection onto the DC busbar.

Another problem with using power electronic converters to supply domestic loads is that the fault current required to blow fuses cannot be supplied. If a fault develops on a piece of equipment then the drive will trip out faster than the fuse will blow due to the limit on drive output current and the very fast response of the drive. One solution to this problem is to include a rotating converter, which could use inertia to supply the required fault current.

11.4.2 West Beacon Farm system
The system installed at West Beacon Farm has a number of areas for further work. The backbone of the system has been installed but the changes listed within this section are still required for improved system operation.

11.4.2.1 Zebra battery
Two main areas relating to the Zebra battery have been highlighted for further work. These are:

11.4.2.1.1 Battery state of charge reset
At present, at least every week the battery must be brought up to 100% state of charge using the back-up generator. This is to ensure that the state of charge displayed does not move too far out of line with the real state of charge.
This could be improved by relaxing the requirement to reset the state of charge. If this was not required as often, it could be scheduled for time when there is no wind forecast.

The control system could be altered to allow wind energy to be exported to the grid during a state of charge reset, which would limit the current into the battery and stop the over-current disconnection, although this would mean the system does not stand-alone.

11.4.2.1.2 Battery voltage range
The voltage of the DC bus bar must be kept within a certain range. Under heavy loads, the Zebra battery voltage will drop below the required voltage range. In this case, the grid drive will import current in order to keep the voltage within the required range. Under high-wind conditions, the current into the battery can be too great and push the busbar voltage to its upper limit. In this case, the grid drive exports any excess energy to the grid.

A stand-alone power system was envisaged but the use of the grid undermines this. The problem is due to both the size of the battery store and the size of the electrolyser, the largest load on the system. Additional battery capacity could be added which would help supply additional current. The size of the electrolyser could be reduced so that the load is reduced. It is recommended that both these options be implemented.

11.4.2.2 Electrolyser
Improvements to the electrolyser have previously been mentioned in section 11.4.1.1. In the West Beacon Farm system, only the option of reducing the stack size is available. The stack could be split into two halves, each with a lower minimum power level, or the number of cells within the stack could be reduced.

If the electrolyser fails, the battery’s state of charge will rise until it reaches 100%. The battery will eventually disconnect, as it will accept no more charge. Either additional controllable loads are required, or some form of energy dump is required to match supply and demand if the electrolyser fails.
11.4.2.3 Wind turbines

As mentioned in section 10.1, the challenge is to maintain system stability in high and turbulent winds. At present, the system performs satisfactorily with relatively high winds but, at times, very high winds cause large currents to flow and the converters can trip out due to either rapid changes or the current magnitude. The converters used to integrate the wind turbines are used in open-loop mode with no feedback. In order to improve their response to the rapid variations in wind power, some form of speed feedback could be used. This could be combined with more interesting drive control, such as torque-mode control, which may improve the dynamic response, although this needs more investigation.

It was also noted that, in marginal wind conditions, the units would generate power if they are motored up to speed, but if they are not motored, they do not reach the speed at which they become aerodynamically efficient and so do not generate. Anemometers could be installed and integrated into the control system to motor the wind turbines up to speed under such conditions.

11.4.2.4 Fuel cells

Both fuel cells must be properly integrated within the system. To do this additional DC-DC converters are required. The long-term operation of the fuel cell DC-DC converter design shown in this thesis must be proven. The efficiency of the unit must be improved along with implementing over-current and over-voltage protection to ensure safe shutdown under fault conditions.

If this cannot be achieved, then commercial units must to be sourced and installed instead.

The Intelligent Energy fuel cell has been designed for combined heat and power use and the heat output could be integrated into the domestic heating supply. This would increase the overall efficiency of the fuel cell unit and may reduce the electrical demand of the heat pump.

11.4.2.5 Grid connection

This system has been designed to be stand-alone. Due to implementation issues with the fuel cells, a grid connection has been required for back-up operation. The
reliance upon this connection must be reduced, as mentioned previously, through the addition of extra storage capacity or by reducing loads. The completion of the fuel cell integration will be of significant benefit in this regard.

As this system supplies a domestic residence, the additional requirement of the grid connection was to ensure system stability even when the Zebra battery disconnected. As mentioned in section 10.8, the current control algorithm within the grid drive becomes unstable when there is no storage element to maintain the DC voltage. This is because the grid drive has been programmed to import and export current. With no battery to buffer the voltage from current variations, the busbar voltage usually stays at the upper or lower voltage limit and any dynamic variation causes the voltage to swing rapidly to the other limit. If the battery does disconnect, the grid drive should switch, rapidly and automatically, to voltage control mode in order to maintain the busbar voltage.

11.4.2.6 TOTEM connection
The power electronics for the TOTEM combined heat and power unit have been installed. Changes to the drive operation are required to ensure that it works in conjunction with the grid connection.

11.4.2.7 Hydro connection
As both hydro turbines generate AC, conversion of power for connection onto the DC busbar should be relatively easy using transformers and rectifiers. The components required to do this have not yet been installed.

11.4.2.8 Solar PV connection
As with the fuel cells, reliable DC-DC converters are required for the integration of the photovoltaic arrays into the DC system. These ought to implement some form of maximum power point tracking.

11.4.2.9 Additional generators
The efficiency of the hydrogen based energy store is lower than using a grid connection. The electrical efficiency of the system as a whole has also been reduced due to a number of additional standing loads, which includes the control and data
acquisition equipment and the electrolyser control circuitry, therefore additional renewable energy generation or energy efficiency measures may be required for an annual energy balance.

11.4.2.10 Deferrable loads
Deferrable loads such as the heat pump or reverse osmosis rig could be used to help match supply and demand.
12 Conclusion

In order to increase the penetration of renewable energy into a stand-alone power system a DC interconnection has been developed, with the loads and generators connected through power electronic converters. The main project aim was to implement and demonstrate such a renewable energy based stand-alone power system, supplying a domestic dwelling. This has been achieved, with wind turbines supplying a relatively high proportion of energy. To integrate the variable renewable energy resource and meet instantaneous demand, both a small battery bank and a hydrogen energy storage system are used.

The power electronic converters separate the voltage and frequency requirements of the devices and gives reasonable power quality to the loads, even with high penetrations of renewable energy. The loads and generators do not need to be synchronised, as would be required for an AC interconnection. The power converters enable stand-alone operation of induction generators within the wind turbines. When compared to an AC interconnection scheme the total number of power converters required is not greatly increased, as the majority of components have differing voltage requirements and hence already contain some form of electronic power converter.

Operational data has been logged over sufficient time periods to demonstrate that such a system is feasible.

12.1 Original contribution

The thesis' original contribution to research centres on the design and engineering of this DC interconnected stand-alone power system and the verification of its operation.

DC interconnection is a standard industrial technique but here it has been applied in a novel way to facilitate the integration of renewable energy sources and energy storage into a stand-alone power system. The principal of stand-alone operation of a wind turbine using a commercial motor drive had been previously proven [86] but the research presented here has shown that this can be applied successfully in a stand-alone system with the increased difficulty of achieving stable operation. The
development of algorithms to achieve long-term operation and automatic control has been covered in detail by this work.

The direct connection of a Zebra battery into such a system has been proven and valuable information on the use of Zebra batteries for stand-alone applications has been gained.

There have been a number of projects involving hydrogen based energy storage systems but the majority of larger systems have been grid connected. The stand-alone operation of an electrolyser has been demonstrated, although the problem of a fluctuating supply to the electrolyser has been highlighted as a major concern.

The converter required for integration of fuel cells onto the DC busbar has been a significant technical challenge and, although the converter topology is standard, practical issues of engineering importance have been highlighted.

The installed components form the backbone of a prototype stand-alone power system that will be used for further projects and research by CREST and other universities.

12.2 General conclusions

The operation of a DC interconnected stand-alone power system has been proven by this research. The general design presented in this thesis has some advantages over other stand-alone systems, but a number of issues still require further research.

The use of standard motor drives and DC busbar is a good solution for the rotating generators and loads. Accurate voltage and frequency control can be used to perform soft-starts and to operate at variable speed to reduce mechanical strain, which may reduce the maintenance requirements of the wind turbines.

The power converters required for the connection of rotating AC devices are standard and hence readily available and cost effective. They also have sophisticated in-built control and are generally quite adaptable.

The main conclusion of this project is that, although such a system is feasible, it is a complicated solution and the long-term reliability of such a system must be proven. The complexity stems mainly from the number of different devices from various
manufacturers. More research needs to be carried out before such a system could be reliably used within a remote community.

'Off the shelf' components have been used whenever possible, but many different components were required, including a number of bespoke units. The system was designed so that components can be easily and safely disconnected for maintenance and adjustment. This led to the requirement for additional DC-rated switchgear, which added to the cost and complexity. The final cost of this project does not make it economically viable in the majority of situations, although it is hoped that, through standardisation and mass manufacture, the costs could be greatly reduced.

Electrolyser technology must be improved to better integrate with variable energy source, specifically concerning its response to variable input power and limited power range. This may reduce or remove the need for battery storage on the system.

Fuel cells designed specifically for connection to such a system would also be required. This could lead to a more electrically efficient storage system.

This work describes an interesting renewable energy system upon which more research can be based. Although feasible, the DC interconnection system requires more research and input from a number of industries before it could be implemented reliably and economically in a remote location.
13 Acknowledgements

This research has relied upon numerous people for a successful outcome. The author would like to thank the following:

Professor Tony Marmont: for supplying the encouragement and the financial means to carry out this research, and allowing his home to be used as a test-bed.

Professor David Infield: for his supervision and guidance.

Murray Thomson: for the initial idea for this project, along with endless help and guidance along the way.

Mick Plowright: for his excellent workmanship and expertise, for imparting so much knowledge and for always having the kettle ready when things were not running to plan.

The whole of the HaRI team: Rupert Gammon, whose vision helped push this project forward, Amitava Roy, who always kept a positive outlook, and John Barton, who was always there to talk through a problem.

Professor Jon Claire, Dr Mark Sumner and others at the Power Electronics, Machines and Control Group at Nottingham University: for freely giving up their time and expertise to help with power electronic design.

Martin Green, Frank Pitt and all involved with this project at Control Techniques.

Roger Bull and Mark Milward at Beta Research and Development.

Wendy, Brian, Des and Ben at Beacon Energy: for their help and good humour.

Angela Marmont: for her tolerance of the disruption caused to her home by this research.

My family and friends: for their support throughout this project and my life.
### 14 Glossary of terms and abbreviations

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOS</td>
<td>Balance of system</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined heat and power</td>
</tr>
<tr>
<td>DC-DC</td>
<td>Direct current to direct current</td>
</tr>
<tr>
<td>HaRI</td>
<td>Hydrogen and renewable integration</td>
</tr>
<tr>
<td>Nm³</td>
<td>Normal meter cubed</td>
</tr>
<tr>
<td>OPC</td>
<td>Object linking and embedding for process control</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
</tr>
<tr>
<td>RE</td>
<td>Renewable energy</td>
</tr>
<tr>
<td>SAPS</td>
<td>Stand-alone power system</td>
</tr>
<tr>
<td>SOC</td>
<td>State of charge</td>
</tr>
</tbody>
</table>
15 Publications by the author


16 References


194


17 List of Figures

Figure 1-1. (a) DC battery systems (b) Wind-Diesel AC systems (c) Power converters and DC systems .............................................................. 2
Figure 1-2. Overview of the installed stand-alone power system. .............................................................. 3
Figure 2-1. Mismatch between renewable energy supply and demand. .............................................................. 8
Figure 2-2. Aggregation of random signals. ............................................................................................................................... 9
Figure 2-3. Typical single-phase domestic load variation [20]. ........................................................................................................ 10
Figure 2-4. Direct connected DC transmission system. ........................................................................................................ 12
Figure 2-5. AC transmission system. .............................................................................................................................. 12
Figure 2-6. The hydrogen cycle. .............................................................................................................................. 19
Figure 2-7. Cost against storage time for various technologies [43]. ........................................................................................................ 21
Figure 2-8. Basic renewable energy based stand-alone power supply. .............................................................. 22
Figure 3-1. Map of West Beacon Farm test site ........................................................................................................ 24
Figure 3-2. Installed wind turbines with close-up. ........................................................................................................ 25
Figure 3-3. Power against speed and torque coefficient against tip speed ratio graphs for the Carter wind turbines. ........................................................................................................ 26
Figure 3-4. Installed PV arrays (tracking and fixed). ........................................................................................................ 27
Figure 3-5. The installed cross-flow and Turgo hydro turbines. ........................................................................................................ 28
Figure 3-6. The TOTEM combined heat and power unit. ........................................................................................................ 28
Figure 3-7. The installed electrolyser process cabinet with close-up of the cell stack. ........................................................................................................ 29
Figure 3-8. The hydrogen storage system. .............................................................................................................................. 30
Figure 3-9. The hydrogen buffer tank, compressor and main store. ........................................................................................................ 31
Figure 3-10. The Intelligent Energy fuel cell, left, and Plug Power fuel cell, right. .............................................................. 33
Figure 3-11. Annual system energy consumption for 2004, showing 1/2 hour averages. ........................................................................................................ 34
Figure 4-1. AC based electrical system. .............................................................................................................................. 35
Figure 4-2. Electrical system using power converters and DC connection. ........................................................................................................ 37
Figure 4-3. Industrial DC-based system. .............................................................................................................................. 38
Figure 4-4. Typical I-V characteristic of an electrolyser cell [6]. ........................................................................................................ 39
Figure 4-5. The Zebra battery. .................................................................................................................................................. 42
Figure 4-6. Electrolyser cycles per year with varying battery capacity. ........................................................................................................ 44
Figure 4-7. Fuel cell and back up run percentage against battery capacity over one year. ........................................................................................................ 45
Figure 4-8. The DC interconnected stand-alone power system for West Beacon Farm. ........................................................................................................ 46
Figure 5-1. The motor drive. .................................................................................................................................................. 49
Figure 5-2. Four-quadrant power flow. .................................................................................................................................................. 49
Figure 5-3. Back-to-back motor drives. .................................................................................................................................................. 50
Figure 5-4. PWM waveforms for DC to AC conversion. ........................................................................................................ 52
Figure 5-5. Electrolyser power electronics, both old AC and new DC. ........................................................................................................ 56
Figure 6-1. Typical IV characteristic of a crystalline solar PV module [41]. ........................................................................................................ 59
Figure 6-2. Typical IV characteristic of fuel cell [60]. ........................................................................................................ 60
Figure 6-3. A basic DC-DC converter .................................................................................................................................................. 61
Figure 6-4. The boost converter. .................................................................................................................................................. 62
Figure 6-5. The flyback converter. .................................................................................................................................................. 63
Figure 6-6. The push pull converter. .................................................................................................................................................. 64
18 List of Tables

Table 6-1. Switching device characteristics [89] ....................................................... 87
Table 8-1. Accuracy of measured data. ................................................................... 135
Table 10-1. Comparison of real data with simulation results................................. 166
Table 11-1. Project costs. ...................................................................................... 174
Table 11-2. Storage cost comparison. ................................................................. 176
19 Appendices

Appendix 19-1. Simulation circuit diagrams ................................................................. 202
Appendix 19-2. DC-DC converter Power circuit diagram ............................................. 203
Appendix 19-3. Wind Turbine Drive DPL Program ..................................................... 204
Appendix 19-4. Electrolyser Drive DPL Program ......................................................... 206
Appendix 19-5. Grid Drive DPL Program ................................................................. 207
Appendix 19-6. The detailed simulation model ........................................................... 210
Appendix 19-7. Zebra battery Simulink model ............................................................ 211
Appendix 19-8. Electrolyser Simulink model .............................................................. 212
Appendix 19-9. Hydrogen energy store Simulink model ............................................. 212
Appendix 19-10. Fuel Cell Simulink model ............................................................... 213
Appendix 19-11. DC-DC Converter Simulink model .................................................. 213
Appendix 19-12. Back-up generator Simulink model .................................................. 214
Appendix 19-13. Control Simulink model ................................................................. 214
Appendix 19-14. Wiring diagram of power electronics added to the electrolyser .............. 215
Appendix 19-15. Wind turbine RPM sensor circuitry .................................................. 216
Appendix 19-16. Zebra DAQ circuitry ................................................................. 217
Appendix 19-17. 24V power DAQ circuitry ............................................................. 218
Appendix 19-18. Electrolyser 4-to-20mA control interface ....................................... 219
Appendix 19-19. IE Fuel cell control interface ........................................................... 220
Appendix 19-20. Grid control interface ..................................................................... 221
Appendix 19-3. Wind Turbine Drive DPL Program.

Initial()
// Initial parameter setup
#8.10=10.01  // Output 1 Source parameter (drive OK)
#8.12=1      // Activate output 1
#8.13=18.31   // Initialise 18.31 (general digital level)
#8.15=1      // Activate output 2
#8.21=18.32   // #18.32 will show the "at speed" indicator
#8.22=0      // do not invert input
#8.16=#18.40  // #18.40 will show whether in test mode or not
#8.09=1      // disable external trips

// Initialise the values for averaging the data
l0opdone%=0   // Sets a counter for the I and V averaging
Vdc_stored=0  // Sets up all the variables to measure V and I
Pac_stored=0

// Place initialise items for the main part of the code here:
#2.21=100     // deceleration rate = 25 sec
#6.01=1       // set stop mode to rampdown
#1.15=1       // Set preset reference = #1.21
#1.14=3       // Set preset ref mode

sl0wdownloop%=0  // Initialise all the counters to zero
switchedonloop%=0
motorisingcounter%=0
slowdowncounter%=0
#1.06=60      // Maximum frequency
#1.07=0       // Sets minimum speed to 0
#5.14=3       // Fixed boost mode (Required to catch a spinning motor)
#6.12=0       // Enable keypad stop key
#18.30=0      // Reset timer value
)

Clock()
IF #10.01=0 THEN // If the has been some trip then...
loopdone%=0     // loopdone=0 therefore initialises again
ENDIF
#18.33=loopdone%
IF loopdone%=0 THEN // If the initial loop should be run then...
#18.31=1       // do not run drive
#4.05=20       // Set motoring current = 29%
#4.07=175      // Set symmetrical current = 100%
#8.06=1        // disable external trips
tripenablecount%=tripenablecount%+1  // increment counter
IF tripenablecount%>18.11 THEN // When at timer value....
loopdone%=1     // flag that the loop has been done
#8.09=0        // enable external trips
tripenablecount%=0/ set the counter back to zero
goto end:  // jump out of initial loop, only to return if there is a trip
ENDIF
goto end: // loop round again until initial timer is done
ENDIF

// The above code is the delay to switch off the brake
// Here is the main code:

// This section is the test mode loop - allows keypad use of drive
IF #8.03=0 THEN
#6.09=1       // Catch a spinning motor OFF
#8.01=1      // Set drive to ramp down
#2.11=100     // acceleration rate = 25 sec
#1.14=4       // Enter keypad control mode
slowdownloop%=0  // Reset all the counters to zero
motorisingcounter%=0
slowdowncounter%=0
switchedonloop%=0  // The part control the motoring current
#4.05=100     // Set motoring current = 100%
goto end:
ENDIF
#4.06=175  // Set export current
#6.09=1   // Set 'catch a spinning motor' ON
#1.14=3  // Set preset reference mode ON
#2.11=100 // acceleration rate =25 sec
#6.10=5  // Rate to ramp frequency to catch motor (s/100Hz)
#6.01=0  // set output to coast to a stop
IF slowdownloop%=1 THEN
  goto slowdown:
ENDIF
IF switchedonloop%=1 THEN
  goto switchedon:
ENDIF
IF #6.05=0 THEN
  #4.05=20  // set motoring current at start (need some motoring current for scan)
  #4.06=175  // Set export current
  switchedonloop%=0
  slowdownloop%=0
  motoringcounter%=0
  slowdowncounter%=0
  goto end:
ENDIF
slowdowncounter%=0
#1.21=50  // Set frequency to 50Hz
#18.31=0 // RUN drive running
switchedon:
switchedonloop%=1
IF #5.04+1450 THEN
  #1.10=0  // regenerating therefore reset this counter
  #4.06=0
  #4.06=175  // Set export current
  goto end: // dont worry about the rest of the program
ENDIF
motoringcounter%=motoringcounter%+1// if not regenerating then count up motoring seconds
IF motoringcounter%<#18.13 THEN // if WT has been motoring then shut down
goto end: // if not then don't
ENDIF
#1.21=43  // Set frequency lower than 'at speed' setpoint
slowdownloop%=1
motoringcounter%=0
slowdown:
#4.06=0   // Set motoring current down to zero
#4.06=175  // Set export current
switchedonloop%=0// go back to switch off loop
slowdowncounter%=slowdowncounter%+1
IF slowdowncounter%<#18.15 THEN
  slowdownloop%=0  // Slow down loop completed therefore reset flag
ENDIF
#18.34=slowdownloop%  // Slow down loop completed therefore reset flag
#18.35=switchedonloop%

ENDIF
#18.31=1  //STOP drive (coast to stop)

ENDIF
// End of main code
// This end must be kept here to ensure initial timer function works
end:

ENDIF
#5.05 < #18.28 THEN
  #18.30 = #18.30+1
ENDIF
IF #18.30 >= #18.28 THEN
  #18.30 = #18.30+1
ENDIF
#18.14=motoringcounter%  // These are to display the values in the drive
#18.16=slowdowncounter%
#18.34=slowdownloop%
#18.35=switchedonloop%

205
This part below averages the various values for C3net data acquisition:

\[ V_{dc\, stored} = V_{dc\, stored} + \#5.05 \]

\[ P_{ac\, stored} = P_{ac\, stored} + \#5.02 \times \#4.02 \times 1.732 \]

\[ L_{stored} = L_{stored} + \#4.02 \times 100 \]

\[ \text{counter} = \text{counter} + 1 \]

IF \#10.01 = 0 THEN

\[ I_{stored} = 0 \]

\[ P_{ac\, stored} = 0 \]

ENDIF

IF \text{counter} \geq 100 THEN

\[ V_{dc\, average} = V_{dc\, stored} / 100 \]

\[ P_{ac\, average} = P_{ac\, stored} / 100 \]

\[ L_{average} = L_{stored} / 100 \]

\[ \text{counter} = 0 \]

ENDIF

\[ \text{clock} \]

Appendix 19-4. Electrolyser Drive DPL Program.

Initial{

top:

\[ \text{counter} = 0 \] // setup a variable called counter and set to zero

\[ \#17.11 = 5 \] // sets clock to 5ms

\[ P_{average} = 0 \]

\[ P_{stored} = 0 \]

\[ I_{average} = 0 \]

\[ I_{stored} = 0 \]

}//Initial

CLOCK{

\[ P_{stored} = P_{stored} + \#5.02 \times \#4.02 \times 1.732 \]

\[ I_{stored} = I_{stored} + \#4.02 \times 100 \]

\[ \text{counter} = \text{counter} + 1 \]

IF \#10.01 = 0 THEN

\[ I_{stored} = 0 \]

\[ P_{stored} = 0 \]

\[ P_{average} = 0 \]

ENDIF

IF \text{counter} \geq 200 THEN

\[ \text{counter} = 0 \]

\[ P_{average} = P_{stored} / 200 \]

\[ I_{average} = I_{stored} / 200 \]

ENDIF

}//Clock
Appendix 19-5. Grid Drive DPL Program.

Initial{
    // The values below initialise the V and I average loops
counter=0; setup a variable called counter and set to zero
counter2=0;
#17.11=5 // sets clock to 5ms
DCset_average=0
DCset_stored=0
DC_average=0
DC_stored=0
ACP_average=0
ACP_stored=0
ACL_average=0
ACL_stored=0
#8.25=#18.31 // Store the input value in #18.31 - displays input bit value
// The values below set up the control functions
current_setpoint=0
pgain=#18.21
igain=#18.22
loopcount=0
loopmax=#18.24
laverage=0
paverage=0
currenterror=0
newvsetpoint=620
integral=0
proportional=0
#18.32=1
stopauto=0
#19.31=0
volegate=0
} // Initial

CLOCK{
    // This part averages the values:
    DCset_stored=DCset_stored+3.05
    DC_stored=DC_stored+6.05
    ACL_stored=ACL_stored+4.02
    ACP_stored=ACP_stored+(5.02*4.02*1.732) // This add up the power
    counter=counter+1
    counter2=counter2+1
    IF #10.01=0 THEN
        ACL_stored=0
        ACP_stored=0
    ENDIF
    IF counter2=200 THEN
        counter2=0
        DCset_average=DCset_stored/200
        #18.11=DCset_average
        DCset_stored=0
        ACL_average=ACL_stored/200
        #18.12=ACL_average
        ACL_stored=0
        ACP_average=ACP_stored/200
        #18.13=ACP_average
        ACP_stored=0
    ENDIF
    IF counter2=20 THEN
        counter2=0
        DC_average=DC_stored/20
        #18.14=DC_average
        DC_stored=0
    ENDIF
    // This is the main control algorithm
    #6.15=#18.32 // Drive runs all the time
    // This is the normal control loop (PI control) it needs a current setpoint
    IF loopcount=loopmax THEN
        // This bit is the over voltage control. The current setpoint will ramp up/down
        // to maintain a certain max voltage.
        IF #5.05='#18.18 THEN
            current_setpoint=current_setpoint-1
        ENDIF

    ENDIF
}

207
IF currentsetpoint<=85 THEN
  currentsetpoint=85
ENDIF

// This bit is the under voltage control. The current setpoint will ramp up/down
// to maintain a certain bottom voltage.
IF #5.05<=(#18.16) THEN
  currentsetpoint=currentsetpoint+1
IF currentsetpoint>85 THEN
  currentsetpoint=85
ENDIF

// This next part is the mid-range, do nothing section. The current should be ramped down here
IF #5.05<=(#18.19) THEN
  currentsetpoint=currentsetpoint-1
IF currentsetpoint<0 THEN
  currentsetpoint=0
ENDIF

// This bit changes to voltage control mode if the battery disconnects
// This can only be reset by switching off the drive then back on again.
IF voltage=1 THEN
  IF #3.05 <= #19.11 THEN
    #3.05 = #3.05 + 1
  ENDIF
  IF #3.05 >= #19.11 THEN
    #3.05 = #3.05 - 1
  ENDIF
  goto misspi:
ENDIF
IF #5.05 > 75 THEN
  stopauto=1
ENDIF
IF #8.05 = 0 THEN
  #18.15 = 0
  stopauto=0
ENDIF
IF stopauto=1 THEN
  goto piprog:
ENDIF

// This bit puts the drive into hold voltage mode when relay is closed
IF #8.05 = 1 THEN
  IF input into drive THEN
    IF currentsetpoint<0 THEN
      goto jumploop:
    ENDIF
    IF currentsetpoint=#18.15 THEN
      goto jumploop:
    ENDIF
    currentsetpoint=#18.15
  ENDIF
ENDIF

jumploop:
// below is the actual PI control loop
piprog:
  laverage=(integral)*(gain/1000)
  currenterror=currentsetpoint-#4.02+(#18.29/1000)
  paverage=(currenterror)*(gain/1000))
  newsetpoint=paverage+laverage+#5.05
  #3.05=newsetpoint
  misspi:
  loopcount=0
  integral=0
ENDIF
integral=integral+#4.02
loopcount=loopcount+1
// Keep the bits below for correct operation
end:
#18.20=currentsetpoint
pgain=#18.21
igain=#18.22
#18.23=loopcount
loopmax=#18.24
#18.25=iaverage
#18.26=paverage
#18.27=currenterror
#18.28=newvsetpoint
voltagemode=#19.31
} //Clock
Appendix 19-6. The detailed simulation model.
Appendix 19-7. Zebra battery Simulink model.

![Diagram of Zebra battery Simulink model]

This is a module based model of the output voltage of the Zebra Battery, coming from data supplied by data sheets.
Appendix 19·8. Electrolyser Simulink model.

Must convert power into current at the stack and use that current to find the conversion efficiency.

Current density in mA/cm² = Current in amps due to cell area × 1000/cm²

Current density = Current in amps due to cell area / cell area

ON/OFF

Setpoint (V)

Standing Load

Appendix 19·9. Hydrogen energy store Simulink model.
Appendix 19·10. Fuel Cell Simulink model.

This is a discrete model of a generic fuel cell. The efficiency is just a constant value.

Appendix 19·11. DC-DC Converter Simulink model.

This is a very simple model of a DC-DC converter. The efficiency of the unit can be selected and is constant. The standing load of the unit is a constant, but only when the unit is running.

Appendix 19-13. Control Simulink model.
Appendix 19-14. Wiring diagram of power electronics added to the electrolyser.
Appendix 19.16, Wind turbine RPM sensor circuitry.

These are smoothing Rs and Cs. Use Rs only if using the DC-DC converter.

This is a DC-DC converter - use if only a unipolar voltage available.

Use this jumper to cut out RMS.

This is a basic circuit with a gain offset from the non-inverting op-amp set by R5 and a variable resistor.

This is a true RMS chip. Refer to data sheet for capacitor values.
Appendix 19-17. 24V power DAQ circuitry.

These are smoothing Rs and Cs. Use Rs only if using the DC-DC converter. 

Use this jumper to cut out RMS

This is a basic circuit with a gain offset from the non-inverting op-amp set by Rs and an variable resistor

These are smoothing Rs and Cs. Use Rs only if using the DC-DC converter. 

Use this jumper to cut out gain and offset

This is a DC-DC converter - use if only a unipolar voltage available

This is a true RMS chip. Refer to data sheet for capacitor values

This is a basic non-inverting op-amp 

This is a true RMS chip. Refer to data sheet for capacitor values

This can be either LT1515-A or LA2941-P

Use this jumper to cut out gain and offset
Appendix 19-18. Electrolyser 4-to-20mA control interface.

![Electrolyser 4-to-20mA control interface diagram]
Appendix 19-20. Grid control interface.