A Power Engineering and Renewable Energy Engineering training facility utilising SMA’s Sunny Island Inverter.

“A report submitted to the School of Engineering and Energy, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering”

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**Declaration of Originality of Research:**

I certify that the research described in this report has not already been submitted for any other degree.

I certify that to the best of my knowledge, all sources used and any help received in the preparation of this dissertation have been acknowledged.

Signed: __________________________________
Abstract:

Murdoch University’s engineering department has conceptualised the development of a training system for renewable energy and power engineering students based upon SMA’s Sunny Island inverter.

The inverter operates using the droop control algorithm in which the control of real power flows alters network frequency and the control of reactive power flows alters the network voltage. By controlling the network frequency, the Sunny Island inverter is able to control the real power flows of other AC coupled inverters on the network. The system provides a simple, safe and localised learning tool whereby students are able to understand and interact with the system to understand the similarities in operation between the Sunny Island network and a large electricity network.

The conversion of the existing system to a Sunny Island system involved the redesign and reconfiguration of a number of existing components in order to ensure compatibility with the new Sunny Island network. A number of compatibility issues were addressed and solutions presented to maximise the use of existing components and implement changes which allow a fully functional system in the future.

A monitoring system was required to maximise the educational value of the system and enhance the visualisation of the Sunny Island’s operational characteristics. It was determined that SMA’s monitoring equipment was not capable of the sample rates required to detect transients in the AC network. A second monitoring system has been proposed utilising high-speed data acquisition equipment that is able to monitor at approximately 100 samples per cycle.

This report sets a precedent for future work related to the training system’s physical development and allows for the continued development of the system into a fully-equipped Sunny Island system which is equipped with photovoltaic, wind and diesel generators; and whose operation can be visualised through the associated monitoring system.
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Thanks also to the Australian Power Institute (API) for their financial grant which was awarded to this project in 2009.

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- Wilhelm Van Butselaar at SMA Australia for his ongoing technical assistance relating to the Sunny Island inverter.
- David Feeney and the team at Solar Matrix (Canning Vale, WA) for their financial assistance relating to inverters and other equipment supply.
- Parisa Bahri as Dean of the School of Engineering and Energy at Murdoch University for her ongoing academic support.
Glossary of terms/List of Abbreviations:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>°</td>
<td>Degrees (directional)</td>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
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<td>DC</td>
<td>Direct current</td>
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<tr>
<td>FSPC</td>
<td>Frequency shift power control</td>
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<tr>
<td>LV</td>
<td>Low voltage</td>
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<tr>
<td>MPa</td>
<td>Megapascals (pressure)</td>
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<tr>
<td>ms⁻¹</td>
<td>metres per second (velocity)</td>
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<tr>
<td>Ms</td>
<td>Milliseconds</td>
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<tr>
<td>NSWTTC</td>
<td>National Small Wind Turbine Test Centre</td>
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<tr>
<td>PC</td>
<td>Personal computer</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<td>RAPS</td>
<td>Remote Area Power Supply</td>
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<td>RISE</td>
<td>Research Institute for Sustainable Energy</td>
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<tr>
<td>RMS</td>
<td>Root mean squared</td>
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<tr>
<td>RPM</td>
<td>Revolutions per minute</td>
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<tr>
<td>SB</td>
<td>Sunny Boy inverter</td>
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<td>SI</td>
<td>Sunny Island inverter</td>
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<td>SDC</td>
<td>Sunny Data Control</td>
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<td>SWIS</td>
<td>South West Interconnected System</td>
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<tr>
<td>VSI</td>
<td>Voltage source inverter</td>
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<td>WB</td>
<td>Windy Boy inverter</td>
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List of Symbols:

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>f</td>
<td>Frequency (electrical)</td>
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<tr>
<td>Q</td>
<td>Reactive power</td>
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1.0 Introduction:

In 2009, Murdoch University’s engineering department was awarded a grant by the Australian Power Institute to develop a training facility for its Renewable Energy Engineering and Power Engineering students. In collaboration with the Research Institute for Sustainable Energy (RISE), a system based around SMA’s Sunny Island inverter was to be developed in order to demonstrate to students the similarities in characteristics of operation between the Sunny Island inverter and a large electricity network while also developing an awareness of different renewable energy resources and an understanding of off-grid energy systems.

In today’s industrialised world, fossil fuels, including coal, gas and liquid fuels, remain the primary inputs to thermal power stations. With an increasing awareness and concern toward the environmental and health effects of these power stations’ polluting properties, there has been a significant investment in the research and development of domestic, commercial and industrial scale renewable energy technologies.

It is stated that 10% of the world’s adult population possess 85% of global household wealth [1], displaying that a large proportion of the world is inhabited by communities living in poverty. These communities are generally located remotely and do not have a permanent connection to their country’s electricity network, creating the need for a permanent power source such as a diesel generator. These diesel generators are expensive to operate and maintain, create significant environmental pollution and can be inconvenient as they are generally only run for the peak load period of the day (early morning and early evening), leaving these communities without electricity for a significant portion of the day. Renewable energy technologies are becoming a suitable alternative to the workhorse of the developing world, the diesel generator. These technologies include solar photovoltaics, wind turbines, small-scale hydro-electric turbines and biomass/bio-digesters (generally fed with animal faeces and farming by-products).
As the need for these renewable energy systems has developed, so too has the technology. An inverter is required to convert the output of these renewable energy generators into a useable form. The requirements of a grid-connected solar inverter in Western Australia are vastly different to that of a community power system’s inverter located in a third world country. Consideration of harsh operating conditions, modularity and low-cost expandability must all be considered in its design as well as the ability to interface with a supply network should the nation’s electricity supply network be extended to reach the village in the future. In cooperation with the Institut für Solare Energieversorgungstechnik (ISET) (a German-based research and development institute for renewable energy technologies), SMA (a German-based manufacturer of inverters and monitoring systems for renewable energy applications) has developed the Sunny Island inverter to meet this market requirement.

The Sunny Island inverter is a battery inverter which forms the basis of a self-sufficient islanded AC microgrid. In the Sunny Island system, all PV arrays, wind turbines, hydro-electric turbines, diesel generators and consumer loads are connected to the AC network, with the only DC connected item being the system’s battery bank. As displayed in figure 1, renewable energy generation sources are connected to the microgrid through SMA’s Sunny Boy or Windy Boy inverters which convert the generation source’s DC output into a grid-quality AC output which is fed directly into the AC microgrid. The Sunny Island uses similar techniques to a large electricity network to control the output of the Sunny Boy and Windy Boy inverters by using the droop control technique.

The objectives of this project are:

- To investigate the operational characteristics of the Sunny Island inverter and thus determine how to incorporate the Sunny Island inverter into display system 2 which is located at the RISE facility (discussed in chapter 4).
- Assess what exists in the current energy system and determine what other equipment will be required to enable interaction with the Sunny Island inverter.
- Investigate and propose a suitable monitoring system which will allow students to gain an understanding of the system’s operational characteristics.
The first section of the report will begin by explaining the basics of droop control techniques and how the Sunny Island inverter applies these to the microgrid. The second section of the report discusses the concept of AC coupling and its associated benefits and disadvantages. The third section of the report will investigate the existing system and how it is to be modified to allow the integration of the Sunny Island inverter. The fourth section of the report will address the training and educational purposes and requirements of the system through the proposal of a monitoring system which will monitor the operation of the Sunny Island inverter and the microgrid as a whole.

Figure 1: Diagram of a Sunny Island system displaying the AC-coupled generation concept [2].
2.0 Overview of Droop control and the Sunny Island’s principles of operation:

2.1 Basics of Droop Control:

Power/frequency and reactive power/voltage droops are well known and widely adopted control methods in large-scale electricity networks. Droop control is described as a method whereby active and reactive power exchange between a generator and the grid is utilised to control the grid’s voltage magnitude and frequency [3].

In order to understand the operation of the Sunny Island’s droop control algorithm, an understanding of governing action in large thermal generating units is useful.

![Governor Model Diagram](image)

Figure 2: A diagram displaying a simplified governor model (Governor displayed in red). Adapted from [4].

The governor model in figure 2 displays the regulating action as conducted in a large thermal power station (e.g., coal, nuclear, etc). The generator is generally a synchronous machine, where the prime mover operates at a fixed speed equal to the generator’s synchronous speed.

Assume that the electrical network has a load of 50MW that has been constant for enough time to allow the rotational speed of the prime mover to stabilise. Under this condition $P_{\text{Load}} = P_{\text{In}}$.

Assume now that the electrical network’s load suddenly increases to 60MW causing $P_{\text{Load}} > P_{\text{In}}$. The initial reaction will be for the prime mover to slow down causing a deviation from the synchronous speed which is seen on the network as a decrease in frequency (The opposite would occur if the load decreased by 10MW, $P_{\text{Load}} < P_{\text{In}}$ causing frequency to increase). This is displayed in figure 4 (a), where, as the load
power increases (x-axis), the frequency (y-axis) decreases. This decrease in prime mover speed is detected by the governor, creating a magnitude of error that is fed back to the steam valve in order to allow more energy into the system in the form of steam. This energy input increases the speed of the turbine to the required level whereby $P_{\text{Load}} = P_{\text{In}}$ for the new steady state.

Woodward (USA) [5] describes that in a situation with no droop control, the prime mover’s governor system will continue opening the steam valve until the required speed is reached. However, the valve will have opened further than required due to the inertia of the prime mover, causing its response time to lag behind the response time of the governor/steam valve. Thus, the speed would be higher than required. For this reason, droop control is implemented.

Woodward (USA) [5] also describes that in isochronous control mode, any error created would cause an isochronous machine to immediately increase output to cater for the extra electrical load on the system. Generally, the largest machine on the network will be in isochronous control mode and would set the frequency of the electrical network. If small generators were set to isochronous control, they would be very unstable as any frequency decrease would cause their governors to operate the machine at full load as it tries to alter the grid frequency, however, its capacity is too small to have any significant impact (as compared with the largest machine on the network). In the case where it detects a frequency increase event, its governor will cause it to unload as it tries to have the system come back to its base frequency (such as 50 Hz). With droop control, however, the machine is fixed to the speed/frequency of the network, thus, the governor control is more precise as the generator cannot increase its speed by a significant amount. As the machine is loaded, the governor will act to increase the machines output to bring it back to the system’s network speed/frequency. As displayed in figure 3, this frequency will not be exceeded.
Figure 3: Difference in behaviour of Isochronous and Droop control governors [5].

Assuming the presence of two voltage source inverters (VSI) in parallel, as per a Sunny Island system with AC-coupled PV and/or wind generation, the following equations represent the flows of real power and reactive power in the system:

Equation (1) – Adapted from [6] and [7].

Equation (2) – Adapted from [6] and [7].

$L_1$ and $L_2$ represent the coupling inductances of the respective inverters. Taking into account $V_1$ and $V_2$ (respective inverter voltages) and $\delta$ (phase shift/power angle between the output of the two respective inverters), it can be implied in equation (1) that power is directly controlled by the power angle $\delta$; and in equation (2) the reactive power flow is directly related to the voltage difference between the two VSI’s.

This leads to a mathematical representation of power/frequency and reactive power/voltage droop control as:

Equation (3) – Adapted from [7].

Equation (4) – Adapted from [7].

Figure 4: (a) and (b) : Droops in a large power system/electricity network [6].
The Sunny Island inverter is programmed with a number of droop control parameters related to equations (3) and (4). These include the inverter’s idle frequency (ie. The grid frequency) ‘f₀’, the idle voltage (ie. the grid voltage) ‘u₀’, the slopes of the droops (frequency as a fraction of rated power – Hz/P₀) ‘-k_p’/-’k_q’, the rated active power capability of the inverter ‘P₀’ and the rated reactive power capability of the inverter ‘Q₀’ [6, 7]. Other parameters include ‘f’ which represents the systems frequency, while ‘U’ represents the system voltage, ‘P’ represents the system’s active power consumption and ‘Q’ represents the system’s reactive power consumption. These values provide a reference from which the Sunny Island bases its droop control algorithm. When the network values deviate from these reference set-points, the Sunny Island’s droop control algorithm acts to return the network values back to these set-points by altering active and reactive power flows.

Figure 4 (a) and 4 (b) above display the Sunny Island’s sloping power/frequency and reactive power/voltage droops which are represented numerically in equation (3) and (4); a change in frequency or voltage are used as signals for the control system to meet changes in power demand [8].

Figure 4 (a) displays that as demand for real power in the network increases, the frequency has a tendency to decrease from the ‘f₀’ set point. As the frequency deviates from this set point, the inverter senses the change in frequency ‘Δf’ and increases power output in order to move the system frequency back to the ‘f₀’ set point. The same occurs in figure (b), where a decrease in voltage is related to an increase in reactive power demand. As the voltage deviates from the ‘u₀’ set point, the inverter senses the change in voltage ‘Δu’ and varies reactive power output in order to move the system voltage back to the u₀ set point.

2.2 Sunny Island Principles of Operation:

SMA’s Sunny Island inverter is an off-grid inverter whose control system operates with similar principles to a large power system. It creates a low-voltage microgrid which contains many of the same principles of operations as Western Australia’s South-West interconnected system, through the droop control algorithm.
Through an understanding of droop control, the Sunny Island’s principles of operation become more apparent. The Sunny Island operates in a similar fashion to a large power system by controlling the frequency of the network through the control of real power flows within the system; the control of voltages in the network is achieved by controlling reactive power flows within the system. Real power flows in the system originate from all AC-coupled inverters including the Sunny Island, Sunny Boy and Windy Boy inverters. The Sunny Boy and Windy Boy inverters, however, operate at a power factor of 1, thus, all reactive power required for voltage control is supplied to the load only from the Sunny Island.

Unlike typical systems where a master inverter controls slave inverters through a separate communication network (Eg. RS232, RS485 or other similar methods), the Sunny Island can operate in a location which is completely remote from the AC-coupled generation source inverters while still providing control of the overall system. By utilising a droop control algorithm, the Sunny Island inverter forms the heart of the island system and dictates the operational characteristics of other AC-coupled inverters in the system (Eg. Sunny Boy, Windy Boy, etc). By utilising frequency changes in the AC network, the Sunny Island is able to control the power output of other AC-connected inverters. These frequency changes also allow the operation of dump-loads which divert excess energy to loads such as water pumps and water heaters in times of excess energy generation. The Sunny Island inverter utilises reactive power/voltage droops to control the system’s voltage.

The Sunny Island utilises a control algorithm titled Selfsync™ whose control strategy slightly alters the conventional droops associated with large electrical networks. In conventional electrical networks, frequency droops are implemented through the measurement of the system’s frequency after-which power outputs are adjusted accordingly. However, due to simplicities in measurement, the Selfsync algorithm measures the output power of the Sunny Island inverter in the system, and alters its output frequency/the system frequency accordingly.

It is to be noted that if two voltage source inverters are connected in parallel, a difference in the phase angle between the two sources will cause real power to flow, where a difference in voltage between the two sources causes reactive power to flow
This displays how the Sunny Island is able to regulate grid voltage and frequency without any communications connections between the inverters. In a study carried out by Alfred Engler, he states that “In expandable distributed inverter systems, communication and/or extra cabling can be overcome if the inverters themselves set the instantaneous active and reactive power [6].” The Sunny Island network benefits by not requiring any communications cabling between itself (which forms the island network and its associated parameters) and other inverters in the system (Sunny Boy, Windy Boy, etc). All inverters in the system contain a reference voltage, reference frequency, parameters identifying the slope of droops and a number of other basic commands [6]. These parameters form the base values from which the droop control algorithm acts to adjust system parameters. All of the AC-coupled inverters including the Sunny Boy and Windy Boy inverters vary their output in response to frequency changes in the network. The network frequency is set by the Sunny Island inverter based upon the load on the system/real power flow (similar to a machine in Isochronous control), and the Sunny Boy and Windy Boy inverters respond by varying their output according to the current frequency of the system (similar to a thermal power plant operating in droop control).

The Sunny Island inverter utilises a control algorithm known as Frequency Shift Power Control (FSPC). FSPC adjusts the output frequency of the Sunny Island inverter based upon the load on the system and the current quantity of energy being supplied from other AC coupled generation sources supplying the system, hence altering the system frequency. AC-connected generation sources (Sunny Boy and Windy Boy inverters) are sensitive to the grid frequency and utilise it as a reference by which to control their output power to ensure that it is limited in times of excess generation. Assume a grid frequency of 50Hz. In the situation where the grid frequency drops below 50Hz, the AC-coupled inverters recognise this decrease due to a lack of generation on the network and thus increase output to the maximum amount available from the renewable energy source (PV modules or wind turbine). In the situation where the grid frequency rises above 50Hz, the AC-coupled inverters recognise this increase as excess generation and thus begin to limit their output, ensuring that the batteries are not overcharged. As the frequency passes a user-programmable set point, the AC-coupled inverters are disconnected from the network to prevent overcharging of the batteries [9].
Figure 5: The Frequency Shift Power Control function illustrated [9].

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<tr>
<td>$P_{AC}$</td>
<td>Stand-alone grid power demand (% of peak)</td>
</tr>
<tr>
<td>$f_0$</td>
<td>Stand-alone grid nominal frequency</td>
</tr>
<tr>
<td>$F_{AC}$-delta - and $F_{AC}$-delta +</td>
<td>Maximum range in which the Sunny Boy is active, based on $f_0$</td>
</tr>
<tr>
<td>$F_{AC}$-start delta</td>
<td>Frequency at which FSPC begins</td>
</tr>
<tr>
<td>$F_{AC}$-limit delta</td>
<td>Frequency at which FSPC ends (i.e. Sunny Boy inverter is disconnected from the network)</td>
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The diagram above displays the operation of FSPC in a graphical format for a Sunny Boy inverter coupled on the AC side of the network. As the network frequency rises past $F_{AC}$-start delta (the user-programmable set point at which FSPC begins limiting the Sunny Boy’s output) the Sunny Boy’s output begins to decrease at a rate specified by the $F_{AC}$-limit delta. It can be seen that as the $F_{AC}$-limit delta is reached, the Sunny Boy decreases to zero output, effectively disconnecting itself from the system until the frequency recovers to an acceptable level.

The Sunny Island controls the voltage of the system by varying the flow of reactive power to the load in much the same way as a generator on a large electrical network transfers or absorbs reactive power in order to maintain the network voltage at its specified set point. It is to be noted that the Sunny Boy and Windy Boy inverters are unable to provide reactive power support, thus, this task is solely placed upon the Sunny Island inverter.
It is to be noted that the Sunny Island has the capability of being a grid-interactive inverter and being connected to a large network if the facility is available. The Sunny Island’s specifications are suited to grid-connection under the Western Power Technical Rules [10]. However, the Sunny Island has not undergone AS4777 testing [11]. It is therefore not approved under AS4777, and hence unable to connect to the Western Australian SWIS. The lack of AS4777 approved testing may stem from the fact that the Sunny Island inverter may not have as wide a range of applications in Western Australia as compared to, for example, Africa (remote communities), or the British Virgin Islands (a large number of small island systems).

One SMA inverter which is able to fill a similar role to the Sunny Island and also maintain its grid-connect ability is the AS4777 approved SMA Sunny Backup. The Sunny Backup inverter allows renewable energy generators to supply the load while allowing the import and export of any energy shortfalls or surpluses. It also powers the loads from a battery bank in the event of grid failure.
3.0 Hybrid Renewable Energy Systems and AC Coupled Generation:

3.1 Overview of Hybrid Renewable Energy Systems:

AC-coupled remote area power supply systems (RAPS) form part of a category of RAPS system known as the hybrid system. The term ‘hybrid’ implies that more than one type of energy generation source is utilised including diesel and/or renewable energy. A number of hybrid system types exist including:

- Series systems
- Switched systems
- Parallel systems
- AC-coupled systems

**Series Systems [12]:** Series systems couple all renewable energy and diesel generators through a DC bus as displayed in figure 6. The series connection of components implies that all power being supplied to the load must pass through an inverter which is connected to the battery bank. This includes energy supplied by the diesel generator (through a battery charger) which must be rectified and converted to a suitable voltage prior to passing through the inverter to the load or back into the battery bank for charging purposes. While this system is simple and allows the diesel generator to be optimally loaded (sized correctly to allow a certain battery charging capacity), the large quantity of energy passing through either the battery bank, inverter or the diesel generator’s battery charger/rectifier incurs significant conversion efficiency losses. Due to the system’s generators and inverter being commonly coupled to the DC bus, frequent cycling of the battery bank is required, reducing its lifetime. It must also be considered that the inverter and battery bank will require sizing to meet the peak load.
Switched Systems [12]: Switched systems are operationally similar to the series system, however, they allow a switch to implement a selection of whether the load is to be supplied with the diesel generator or by the battery bank and inverter. This allows higher conversion efficiencies while the diesel is running as it can supply the load directly (avoiding conversions efficiencies related to the inverter and battery bank in series systems) and divert any excess generating capacity to the battery charger which ensures optimal diesel loading. However, the generator is generally sized to handle the peak load, thus making it less efficient due to part loading situations, such as when the load is greater than the inverter’s output capacity but less than the diesel generator’s maximum capacity. The switching action can also provide momentary loss of power to the load.
**Parallel Systems [12]:** Parallel systems build on the series and switched system principles by DC connecting all renewable generators and allowing the battery bank inverter to synchronise with the diesel generator which is connected to the same AC bus as the loads. In doing so, conversion efficiencies are increased as the diesel generator can supply the load directly or supply the battery bank through a bi-directional inverter. The system is able to supply a peak load equivalent to the sum of the generator and inverter’s outputs, meaning that inverters and generators of smaller capacity can be used, thus reducing cost and optimising their loading. The system, however, is still limited by power conversion efficiencies related to the bi-directional converting action of the inverter/charger.

![Parallel hybrid system](image)

*Figure 8: Parallel hybrid system [12].*
3.2 AC Coupled Generation:

AC coupled generation is a concept whereby the generation sources (such as PV, wind, hydro-electric, etc) are connected directly to the AC network through a grid-connected DC to AC sine-wave inverter without the use of any intermediary storage devices such as batteries. In the Sunny Island network (a sample system displayed in figure 9 above), the Sunny Island forms the basis of the AC network by setting the network frequency and controlling power flows and voltages within the network. The PV generation is connected through an SMA Sunny Boy inverter, and the wind turbine generator is connected through an SMA Windy Boy inverter. Diesel generation is connected directly to the AC network through a relay in the Sunny Boy inverter.

AC coupling is useful in situations where customers and potential resources (solar, wind, hydro, etc) are located remotely as generation sources can be located where the resource is most abundant, or can be located at the extremes of networks in order to reduce transmission losses and strengthen these end-of-grid locations.
The SMA Sunny Island also forms the basis of an extremely modular system in that it can theoretically be a small network with a battery bank and diesel generator to begin with. Over time it can be expanded to include renewable generation sources such as PV, wind and hydro electric turbines; and it can be connected to primary electricity networks as transmission lines are expanded (assuming it meets the network’s technical requirements). This forms an ideal basis for elementary systems in third-world and developing nations which can be expanded as their requirements and financial means develop.

AC coupled generators provide a distinct advantage over the traditional method of connecting low voltage (LV) generation sources to DC storage devices such as batteries, prior to being converted into AC by an inverter. Advantages include [13, 14]:

- **Efficiency gains:** AC coupled generation eliminates the need for a battery bank prior to feeding into the AC network which leaves the generated power open to efficiency losses only in the inverter. Modern inverters are in the order of ~95% efficiency or greater.

  In a DC coupled system, losses would be present firstly in the charge controller/regulator, in the battery bank and again in the inverter.

  If energy is consumed at the same time it is generated (eg. air conditioning loads being fed by PV generation during the day), efficiency gains can be realised as the energy produced is consumed directly by the load (no requirement for energy transfer from the battery bank to the network through the Sunny Island), and thus, the only conversion is from the generator, through the inverter and to the network.

- **Strategic location of generation and loads on the network:** An AC coupled system has the potential for generation to be connected at any point on the AC network. This allows for flexibility in locating PV cells in the most sun-exposed location, such as atop buildings or structures which are away from the cover of trees and vegetation; and would allow for the optimal siting of wind turbines in locations which are exposed to constant and non-turbulent winds (generally atop a hill, ridge or embankment). AC coupling reduces cable losses by locating the inverter close/immediately adjacent to the generation source, allowing its voltage to be immediately raised (to 240V) and fed directly into
the network. Before passing through the inverter, a DC generation source would require the cable to be run to the battery bank, which is most-likely to be located remotely to the generation source. The positive effects of strategically locating generation in a DC system may therefore be negated by cable losses present in extended cable-runs.

- **Ideal in locations with distributed consumers and generation:** In remote communities, transmission losses could become significant if a large central system were distributing energy to users who are remote (not concentrated in a central village, for example). However, by splitting this large system into smaller systems strategically placed on the network in locations which are closer to the consumers, energy losses can be minimised while still allowing users to have access to the same amount of energy (assuming the resource is equally available in these locations). The elimination of control cables for communications allows for remotely located generators on the network to be utilised, thus allowing the likes of solar arrays and wind turbines to be a theoretically infinite distance from the Sunny Island inverter while still being capable of feeding grid-quality electricity into the network.

- **Smaller cables:** Cost savings can become significant in utilising smaller cable sizes across the network. Due to the higher voltage output present in AC coupled systems, cable losses are reduced, resulting in a need for cables with smaller cross-sections. It is also to be noted that generally, DC generation sources are designed to feed into a battery bank which is in the order of 12 – 48V, thus, the size of cable required increases due to large current flows associated with these low voltages. However, SMA’s Sunny Boy inverters have an input voltage window of up to 400V (SB1100/1700), allowing for the possibility of larger string voltages which decreases cable sizes. The Windy Boy inverters have an input voltage window of up to 400V (WB1100/1700) allowing for wind turbines with larger transmission voltages to be utilised, thus reducing cable losses and negating the need for large cables.
- **Installation/appropriate staff:** As the system is operating at standard grid voltages (240VAC) and is alternating current, it can be installed by any qualified electrical contractor. There are no requirements for precautions that may be present with high-voltage networks, and the use of DC protection and isolation equipment is reduced. DC equipment is not as widely understood as AC equipment. This would allow for a simple future expansion of the system.

- **Quantity and size of generation:** In a large system, it may not be feasible to connect large amounts of DC generation to a battery bank due to efficiency losses. An AC-coupled system would allow larger generators to be connected as all energy supply to loads takes precedent over battery charging. Due to efficiency losses being lower in a generator/inverter system as compared to a generator/battery/inverter system, this may prove beneficial in large remote networks.

- **Expandability/modularity of system:** The AC network can be as simple or as complex as desired by the system designer. It can incorporate only a battery bank and diesel generator to begin with, following which it can be expanded to include further renewable energy sources. Single phase to three phase expansion is also possible as power demands increase. This is ideal for financially-poor or third-world communities which may wish to stage the development of their system, and/or expand it as their requirements develop over time to include items such as lighting in village homes, refrigeration, water desalination plants, etc. The system can be scaled up to a total of approximately 100kW.

- **Redundancy** – Figure 10 below displays how multiple Sunny Island inverters can be connected in a three-phase system through an SMA Multicluster Box to increase the systems overall capacity. “Clusters” are groups of interconnected Sunny Island inverters which feed into the AC network from a battery bank – They are generally used in three-phase systems. Master/slave communication must exist between the clustered Sunny Island units. The system can contain a number of geographically distributed clusters, as long as they are connected by the appropriate communications cables. In the situation where multiple
clusters of Sunny Island inverters exist, any cluster can take up control of the network should there be a failure in the main cluster. In the event of a failure, any AC-coupled Sunny Boy and Windy Boy inverter can continue to supply the AC network no matter where it is located (this is due to the fact that these inverters use FSPC as the power control method, rather than physical communications cables). Although the system’s overall capacity is reduced due to the failure, its ability to supply the loads is not completely hindered. In a fully interconnected master/slave arrangement, the failure of the master inverter would cause the whole system to go offline. This feature is important in remote locations where skilled service staff or replacement items are difficult to obtain and may cause a master/slave system to remain offline for significant periods of time.

![Figure 10: Clusters of Sunny Island inverters in a three-phase system [15].](image)

- **Cost savings:** Cost savings in both installation labour and hardware are realised due to a lack of communications connections between AC-coupled inverters. Maintenance costs due to damage of cables from vermin or otherwise can also be eliminated.
- **Effects on battery banks:** In general, a system’s load demand is greatest during the day-time, with overnight loads generally being small and relatively constant (apart from an evening peak). In an AC-coupled system, power from generation sources is firstly fed to loads as a priority, with any excess then being fed into the battery bank. In a DC-coupled system, all power into and out of the system would transfer through the battery bank. This could cause significant strain on the battery bank and may cause increased wear due to cycling. Thus, an AC-coupled system could potentially extend the life of an attached battery bank as compared to a DC-coupled system.

AC-coupled generation also has its disadvantages:

- **Cost:** Instead of utilising a central inverter, each generation source on the network requires its own inverter where a DC-coupled generation source would only require a charge controller. Some generation sources such as wind and micro-hydro turbines may even have these integrated by the manufacturer. According to www.energymatters.com.au, an Australian online renewable energy equipment store and at the publication date of this paper, inverter costs were in the order of thousands of dollars per unit (~$1.30 per watt), whereas charge controllers were in the order of several hundred dollars per unit ($0.50 per watt).

- **Stored energy efficiency:** If the energy is consumed at times when it is not being generated (such as energy which was generated by PV and stored in the battery bank during the day, then being used at night for lighting loads), efficiency losses can be significant as efficiency losses are present in the conversion of DC electricity to AC electricity between the DC generation sources and the AC network (through the Sunny/Windy Boy inverters), again in the conversion of AC electricity to DC electricity (from the network, through the Sunny Island and into the battery bank) and again when converting the battery bank’s energy into useable AC energy.

- **Equipment restrictions:** Currently, only SMA equipment is compatible with the Sunny Island network. No other inverter types can be connected. This
leaves no room for competing inverters to regulate price, thus, the system could be out of financial reach for a number of poverty-stricken communities.

- **Safety**: In a Sunny Island system, there is no islanding control in relation to the ac-coupled generation source inverters. If the Sunny Island goes offline due to a fault, the Sunny Boy and Windy Boy inverters will remain connected to the network in an islanded state if the network conditions allow it to do so. This can cause a significant safety concern for staff who are unaware of this situation, or unfamiliar users that may be new to maintenance and operation of the system.
4.0 The Existing System, Proposed System and Associated Problems:

The base system (known as system 2 at the RISE outdoor test area) was an operational hybrid remote area power supply (RAPS) system which formed part of a display system at the Research Institute for Sustainable Energy’s (RISE) outdoor test area.

The system consisted of [16]:

- Solar photovoltaic (PV) array (1.232kW) - 16 Solarex 77W PV modules.
- Solar charge regulator – Plasmatronics PL40
- Associated PV array frame – Non tracking.
- Wind turbine – Westwind 3kW (48V) mounted on an 18 metre guyed tubular tower. Included a Westwind controller/battery charger with associated dump loads.
- Diesel generator – 5kVA. Robin DY41D pull-start motor with Modra generator/alternator.
- Inverter – Power Solutions Australia RAP-3-48-1 generator interactive sinewave inverter rated to 3kW @ 48V.
- Battery bank – 1080 Ah @ 48V consisting of 8 Exide Energystore 6RP1080 flooded lead acid batteries connected in series.
- Typical household loads such as water pumps, heaters, air conditioners, lights, etc are present within the display system. A programmable load bank is also present.

The new system aimed to utilise as many components as possible from the existing system including the PV array, wind turbine, diesel generator, battery bank and loads. However, due to the new system architecture, a full redesign of the system was necessary including reconfiguration of the PV array, an upgraded wind turbine and a redesign of the electrical system to suit the new inverters. The Power Solutions Australia inverter became obsolete following replacement with the Sunny Island inverter.
Solar PV:

Originally, the PV array was wired to have a rated voltage of 48V which suited the battery bank – The arrangement included 4 strings of 4 series connected modules. The new system, being AC coupled, utilises an SMA Sunny Boy SB1100 inverter which has a maximum power point tracking input voltage window of 139V – 320V. The array was rewired to suit this window, namely, a single string of 14 PV modules in series, forming an array of 1078W with a maximum operating voltage of 315V (occurring at $T_{min}$ of 5°C and assuming no cable losses). This array is slightly derated from the original array configuration. The original DC charge controller has now been eliminated.

Wind Turbine(s):

AC coupling of the existing 3kW Westwind wind turbine would not have been possible without utilising an SMA Windy Boy inverter. However, the voltage window of the appropriate Windy Boy inverter is 200V – 500V which is greater than the 48V output of the wind turbine. This created several issues in that:

- A 48V Windy Boy inverter would not have been able to handle the 3kW output of the turbine as the inverter is only rated to 1.1kW.
- A step-up transformer capable of handling the wind turbine’s output would have been prohibitively expensive.
- While possible, connecting the wind turbine on the DC side of the system would not provide as much educational value as AC coupling would, thus, this option was eliminated.

Several options were presented (see table 1 below) in order to allow for wind generation in the system, including:
<table>
<thead>
<tr>
<th>Option</th>
<th>Turbine Type</th>
<th>Size</th>
<th>Notes</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3kW Westwind</td>
<td>3kW</td>
<td>(Rewind to 260VAC + Labour) + Windy Boy 3.8kW + WB protection Box 500 (AU$3000) + AU$3109 + $2268 (WW controller exchanged for WBPB)</td>
<td>8377</td>
</tr>
<tr>
<td>2</td>
<td>3kW Westwind</td>
<td>3kW</td>
<td>3x WB1100LV inverters + WBPB/Current controller 3 x $1422 + $2268</td>
<td>9315</td>
</tr>
<tr>
<td>3</td>
<td>Airdolphin</td>
<td>1kW</td>
<td>AirDolphin + WB1100LV + 120Ah battery bank + Circuit breaker $5940 + $2349 + $525 + $13.65</td>
<td>8827.65</td>
</tr>
<tr>
<td>4</td>
<td>Damaged</td>
<td>TBA</td>
<td>Whisper H40</td>
<td>TBA</td>
</tr>
<tr>
<td>5</td>
<td>3kW Westwind</td>
<td>3kW</td>
<td>DC connect directly to the battery bank</td>
<td>Nil</td>
</tr>
<tr>
<td>6</td>
<td>1kW Soma</td>
<td>1kW</td>
<td>1kW Soma + WB1700 6800 + 1813 = $8613 inc GST</td>
<td>9457</td>
</tr>
<tr>
<td>7</td>
<td>Fortis Passaat</td>
<td>1.4kW</td>
<td>Pasaat + WB Protection box + Windy Boy 1100LV + 40A slip rings 5313.50 + 2435.85 + 2680.65 + 1443.20 = $11 873.20</td>
<td>11873.2</td>
</tr>
<tr>
<td>8</td>
<td>Ginlong Show</td>
<td>15A</td>
<td>Show 15A + Windy Boy 1700 7149.20 + 1812.98</td>
<td>8962.18</td>
</tr>
</tbody>
</table>

Table 1: Wind Turbine options.

**Option 1: Rewinding the existing 3kW turbine to be grid-connect compatible.**

This would involve labour to lower and raise the wind turbine as well as transport it to and from the rewinder’s workshop. The existing 48V Westwind controller would have become obsolete and would require replacement. In discussions with Westwind, testing of the Windy Boy Protection Box (SMA’s wind turbine rectifier and dump load controller) had indicated that it was not suitable to use with Westwind turbines due to it having an on/off style dump load control. That is, as the turbine’s output reached the voltage and power limits on the inverter, it would simply switch a dump load in without the use of any pulse-width-modulation (PWM) techniques. Westwind stated that their controller used PWM in order to progressively switch in dump loads, which placed less stress on the wind turbine. The cost of the new controller was quoted at approximately $3700. Due to warranty issues, Westwind would not allow the use of a Windy Boy Protection Box with their wind turbines. However, the warranty on the wind turbine had expired. For this reason, a cost saving was incurred by selecting the Windy Boy Protection Box instead of a new grid voltage compatible
Westwind controller. The estimated cost of this option, including a new SMA Windy Boy WB3800 would be $8377. It is to be noted that the reliability of this turbine would be lower than a new option due to it being an aging machine. No value was placed on reliability or possible maintenance cost escalations due to the machine’s age.

**Option 2: Utilising several paralleled low-voltage inverters to grid-connect the existing turbine.** This option involved using three low-voltage model Windy Boy inverters (WB1100LV) in order to feed the turbine’s 48V output into the grid. Three were used due to the maximum output rating of these low voltage inverters being 1.1kW – SMA does not have any low voltage inverters of a higher output rating. It was envisaged that issues could arise with complexities associated with the paralleling of these inverters from one source. The cost of this option ($9315) was greater than option 1 and still presented the issue of utilising an aging and potentially unreliable turbine. In the case where one inverter fails, the system will require disconnection as the two remaining inverters would not be capable of handling the wind turbine's full output under high-wind conditions. The possibility to limit the turbine’s output would be limited without active stall control built into the turbine, thus power electronics (such as a pulse-width modulated dump load) would be required to limit input currents to the inverter. This would add to the already prohibitive cost of implementing this option.

**Option 3 (New turbine option): Zephyr Corporation’s AirDolphin.** The Zephyr AirDolphin is a Japanese-made 1kW small wind turbine which is available in both a grid-connect and battery charging model. This new turbine option was investigated. The turbine utilises a nacelle-mounted rectifier/controller which posed issues in which the wild-AC output of the turbine could not be monitored by any standard sensors. Necessary modification of the wind turbine would have voided the turbine’s warranty, causing this option to be ruled out. At $8828, this new turbine option would have been cost-competitive with options 1 and 2. Being a new machine, the reliability of this machine would have been significantly greater than the Westwind turbine presented in options 1 - 3. These costs assumed that the existing Westwind turbine’s tower could be used to mount the AirDolphin wind turbine, however, should the tower have a different coupling method to the Airdolphin or the tower be unsafe for ongoing
use, a new tower would need to be purchased. A value of approximately $5000 should be budgeted to replace the tower.

**Option 4: Repair and recommissioning of a damaged wind turbine.** Murdoch University owns a damaged Southwest Windpower Whisper H40. The wind turbine suffered significant damage to itself and its tower when it fell to the ground in an incident caused by excessive vibration. The turbine is currently in an irreparable state, and thus was excluded as a replacement option for the Westwind wind turbine.

**Option 5: DC connect the existing 3kW wind turbine.** This option involved connecting the wind turbine directly to the 48V battery bank, negating the need for an inverter or the purchase of other equipment. Although this would have added extra generation to the system, it would not provide any significant educational benefit. This option was ruled out and would have only been used as a method of last resort. The wind turbine is currently DC connected to the same battery bank that would be utilised in the new system. Theoretically, minimal further cost was required to implement this option with the only additional requirement being a simple current shunt connected across the battery bank. This shunt allows the Sunny Island to monitor what quantity of energy is being fed into the battery bank by the wind turbine. However, this option has the potential to cause problems with the Sunny Island inverter’s battery charging regime as it is unable to control the quantity of energy being fed into the battery bank by the DC connected wind turbine.

**Option 6 (New turbine option): Soma Power 1kW turbine connected through a Windy Boy WB1700.** At the time that the wind turbine issues were being investigated, the National Small Wind Turbine Test Centre (NSWTTC) located at RISE was in possession of a Soma Power 1kW wind turbine for testing purposes. The Soma wind turbine is an Australian-made 1kW downwind-facing wind turbine. It was anticipated that this turbine could potentially be used. However, there would be times when the wind turbine would be unavailable to the system due to testing requirements, and thus the wind component of the system would not be available for educational use. This was determined to be an unacceptable compromise, causing this option to be eliminated.
Option 7 (New turbine option): Fortis Passaat 1.4kW connected through a Windy Boy WB1100. The Fortis Passaat is a 1.4kW Danish-built small wind turbine. The NSWTTC was interested in testing this turbine. Thus, by combining resources, the university and the test centre determined that this turbine could form the basis of the system’s wind component while also being utilised for testing by the NSWTTC. This turbine has been ordered by the NSWTTC and will be installed by the NSWTTC. Connections to the inverter will be in coordination with the appropriate staff who are commissioning the new Sunny Island system.

Option 8 (New turbine option): Ginlong Show15A connected through a Windy Boy WB1700. The Ginlong Show15A is a Chinese-built, 5 bladed, small wind turbine. Again, as with the Passaat, it was determined that the turbine could be used for both educational purposes as well as for testing. The turbine has been ordered and will be installed as per the Passaat.

A BergeyXL1 wind turbine was also investigated. However, this turbine had a nacelle mounted rectifier and only 2 slip rings which made monitoring of the wind turbine’s wild-AC output a difficult task. For this reason, the Bergey XL1 was eliminated from further investigation.

The final option chosen was a combination of the Ginlong Show15A and the Fortis Passaat. These wind turbines will be feeding into the AC system using one Windy Boy WB1700 1.7kW inverter. It is to be noted that this inverter is in fact a Sunny Boy SB1700 inverter, that has been loaded with the Windy Boy control software. The internal electronics of both inverters are identical. However, their control software provides a differentiation between the two; in essence, making it a Windy Boy inverter with Sunny Boy inverter markings.

Due to testing requirements on both turbines by the NSWTTC, it is anticipated that one will always be available for the display system, thus, only one WB1700 inverter has been purchased to allow for the connection of either turbine when the other is being used for testing purposes. Their connections can be easily swapped over by either using a transfer switch, or by the physical swapping of connections by qualified staff members as and when required.
These wind turbines will be installed in cooperation with the NSWTTC for educational use in the Sunny Island system and for testing purposes within the NSWTTC.

**Diesel Generator:**

The diesel generator is currently a manually operated electric-start unit. The Sunny Island inverter has the provisions for full generator management including start-up/shutdown, minimum/maximum run-times and the ability to start the diesel generator during excess load demand on the inverter.

It is anticipated that the system will be equipped with an electric-start diesel generator in the future. Several options were explored, including:

- **Retrofitting the existing unit with an electric starter:** This option proved to be mechanically difficult and costly in comparison to an engine replacement. The appropriate flywheel crown would need to be reached with a custom-mounted and possibly custom-designed starter motor. This would have been both time consuming and costly. It was estimated that the cost of retrofitting an aftermarket electric starter would have been too expensive in relation to the cost of a new or replacement diesel generator, and the appropriate staff may not exist on campus. Thus, this option was eliminated from any further consideration.

- **Exchanging the motor for an electric start unit:** This method would have been the simplest and most appropriate retrofit option. No modifications would have been necessary as the motor shaft could connect directly to the existing generator’s coupling point. It is also to be noted that Robin Diesel (the manufacturer of the existing motor) had a suitable electric-start replacement for the existing motor, allowing for an easy and quick exchange which could be performed without the use of specialised skill-sets. The existing pull-start
motor would remain available as a spare if required. This option was in the order of approximately $4500 plus labour.

- **Purchasing a new electric-start generator:** A new generator is the most expensive option, however, it provides the system with the most beneficial outcomes. It would be a more reliable machine than the existing unit (being a new machine), its controller would already have the provisions for external remote start signals (from the Sunny Island) and it may include a sound-attenuated enclosure. Further investigations prior to purchasing could ensure that the diesel generator’s capacity is more appropriately sized to the system as compared to the current unit. SMA specifies that as a rule of thumb, generators connected to Sunny Island inverter systems should be rated to between 80% and 120% of the system’s peak load capacity. For example, in a system with two SI5048 5kW inverters, the system would have a peak load capacity of 10kW thus the generator should be sized to between 8kW and 12kW.

A diverse range of diesel generators exist on the market. A number of mass-produced Chinese-made products are becoming available at minimal cost. However, their design and construction is questionable due to the use of poor quality components such as inferior rubber fuel lines and radiator hoses. For this reason, the use of a cost-effective machine sourced from a reputable manufacturers such as Yanmar, Robin or Onan will be used. These machines are frequently used in off-grid situations as a permanent power supply, such as in remote homes, caravans and recreational yachts.

Initially, a budget of approximately $7000 - $10 000 was to be allowed for depending on the machine’s size and specifications. This budget was sufficient to obtain a unit from a reputable manufacturer with a capacity of approximately 5 – 7kVA, which would have been mounted in a sound-attenuated and weatherproof enclosure.

A new diesel generator option became available late into the project. RISE is currently in possession of a WTD Australia model WTGS6800DE 5kW electric start diesel generator which was part of a past RISE biodiesel project.
The unit could potentially be compatible with the Sunny Island inverter and its use is to be explored further.

**Battery Bank:**

From past experience with the existing system, the battery bank was deemed suitable to the system’s requirements and was not altered from its original design and installation.

Due to its age, the battery bank should be monitored and replaced in the future, if required.

**Loads:**

The loads within the display system are based around a typical home. Resistive, capacitive and inductive loads are provided including heaters, fans, a refrigerator, a computer (also used for system monitoring), lighting, an air-conditioner and a water pump.

All loads apart from the heater and the air-conditioner are switched through the use of a programmable PLC and associated relays in order to simulate a typical Australian household’s energy consumption pattern. The air-conditioner and heater have been disconnected due to their large power consumption placing a significant demand on the system. They are only used as manually switched items.

The PLC can undergo a full manual override if required.
5.0 Monitoring system

The monitoring system presented several issues in what currently exists in the system and what was required to be monitored for educational purposes in the new system.

In order to understand the operation of the Sunny Island’s power-flow control algorithms, a monitoring system was required that was capable of measuring key parameters in the system. Frequency and power flows were measured to see how they were related, as were the related quantities of reactive power and voltage. Voltage and current waveforms were also to be considered for showing power conversion actions of power converters and the power quality of various pieces of equipment.

The existing monitoring system was insufficient for the project’s requirements. Its focus was on meteorological data, and only power flows in the system were measured. A redesign of the system was required to facilitate and maximise visual presentation of the system’s operation for educational purposes.

The following diagram displays the new monitoring concept in which real and reactive power flows, frequency, efficiencies and waveforms are measured.

Figure 11: Monitoring system design.
Reasons for monitoring:

**Voltage and current:** Volts and currents within the system allows power flows to be calculated. By understanding power flows into and out of power converters such as the inverters and wind turbine controllers, the conversion efficiency can be determined. This will provide an educational benefit by displaying that power electronics have losses associated with the conversion process.

The voltage and current from the inverter into the battery bank will also allow the Sunny Island’s charging regime to be displayed in a graphical format. A range of other educational benefits exist.

**Waveforms:** Provisions to connect an oscilloscope will be provided so that voltage and current waveforms can be observed before and after power converters. These waveforms will display:

- Wild-AC output of the wind turbine (Single phase only - It is assumed that output is balanced across the three phases, thus for simplicity, only single phase measurements will be taken).
- Rectifying action of the wind turbine controller
- Power conversion from DC to AC in each inverter
- DC input from the battery bank to the Sunny Island inverter which will show whether any ripples exist on the DC side of the inverter due to the high frequency switching action present in the inverter’s power electronics and a 100 Hz ripple present due to the inverter being a single phase unit.
- The waveform of the diesel generator to determine whether its output is or is not “clean” i.e. a pure sine-wave.

**Power factor:** The power factor at various points on the AC part of the system are to be measured to determine reactive power flows. These reactive power flows affect the voltage within the system – This is also to be displayed for educational purposes. It is to be noted that the power factor of the existing generator is not measured as this is fixed at 0.8.
5.1 Existing system:

The existing monitoring system consisted of a number of sensors measuring the system’s power, voltage and current flows as well as meteorological data associated with the system. These sensors were then connected to a data acquisition unit, namely, a National Instruments FP-1601 field point unit. The data from this field point unit was read, processed and displayed on a local computer using a custom-designed LabVIEW program. The program also had the ability to display this data on the information portal of RISE’s website where the public could download the information or track the system’s current state of operation.

Appendix B provides a list of all sensors and measurement parameters present in the existing system.

5.2 NEW MONITORING SYSTEM:

A significant part of the new monitoring system can be implemented by utilising SMA equipment. However, a number of specialised measurements will require the use of specific non-SMA monitoring equipment.
SMA’s Sunny Web Box is a data acquisition unit designed to monitor operational performance and diagnose any potential problems within a system. The Sunny Webbox reads and logs data from each of the inverters in the system including the Sunny Boy, Windy Boy and Sunny Island inverters, as well as other SMA monitoring equipment such as the Sunny Sensor Box (SMA’s performance monitoring tool). This data can then be analysed and stored using SMA software which will be discussed below. The Webbox also has the ability to adjust inverter parameters. For example, the Sunny Island allows full control of all system parameters including but not limited to the grid-connection operating parameters, generator control and system setup. These can all be adjusted through the Sunny Webbox and SMA’s Sunny Data Control software. The Webbox connects to the Sunny Sensorbox and Sunny Boy, Windy Boy and Sunny Island inverters through an RS485 connection.

The Sunny Webbox also provides a means by which to monitor system performance in conjunction with the use of SMA’s Sunny Sensorbox. The Sensorbox has an inbuilt solar PV cell which provides a reference for the system’s PV array to be compared to. Based on solar irradiation and cell temperature measurements, the reference cell calculates the output to be expected from the PV array and then compares this to its
current output (through the inverter). A lack of system performance can be detected and brought to an operator’s attention to be rectified in order to prevent damage to the system (eg. due to an electrical fault, etc) or loss of energy generation revenue (eg. from shadowing, dirty/contaminated array surfaces, etc). A performance ratio is determined (a comparison of current energy production to potential energy production) which identifies whether any part of the system is not performing as it should. The Sensorbox is also able to monitor wind speed, ambient temperature and PV module temperature in order to improve the accuracy of its performance calculations. The Sensorbox communicates with the Sunny Webbox through an RS485 connection.

The data is displayed by two methods: firstly, SMA’s Sunny Portal software and also through SMA’s Sunny Data Control software.

- SMA’s Sunny Portal software is a free-of-charge web-based software that allows system data recorded by a system’s Sunny Webbox to be collected, archived and displayed in a personalised and user-friendly manner. This data relates only to the solar PV generation. It allows the visualisation of system performance utilising numerical displays such as charts and tables. These can be generated and displayed on a webpage which is specific to the system and available to both system operators and to the general public. System operators are able to devise how system parameters (eg. peak and cumulative output, output of the plant in real-time, CO₂ savings, revenue, etc) vary with output, and how the system is performing overall. It also allows system operators to log any system event messages such as faults, failures, warnings and errors or a lack of performance which would indicate problems with PV modules, an array, or inverters. The Sunny Portal is also able to send these details by email to system operators [18].

It is to be noted that the Sunny Portal only displays solar PV system data, hence, our Sunny Island and Windy Boy inverters could not be monitored using this software.

- The Sunny Data Control software takes a more complex approach to monitoring and is suited to the advanced user and for the system’s educational requirements. It is a PC based software package which records data from SMA
inverters in the system through the Sunny Web Box and displays and archives available inverter data locally on the PC. This data can then be exported to the Sunny Portal or monitored locally or remotely by system operators. It provides the opportunity to view the system as a whole, or to disaggregate the system into its individual components including the Sunny Island, Sunny Boy and Windy Boy inverters; while allowing the analysis and modification of each of their parameters.

Measured data in the Sunny Data Control software includes:
- Solar array voltage and current outputs (i.e. inverter inputs)
- Inverter output current and voltage
- Inverter output frequency

Limitations of the Sunny Data Control software include:
- No reactive power or power factor measurements
- Unable to display inverter output waveforms
- Its sample rate is not fast enough to capture and display transient inverter output behaviour.

However, the simple relationship between frequency and real power flow can be observed and understood using the Sunny Data Control software, thus providing an ideal method of displaying how the Sunny Island controls power flows through frequency shift power control (FSPC).

A sample screenshot of each program’s display is included in appendix C.

The Sunny Webbox is the central component in the SMA monitoring system. It acquires data from the inverters and from the Sunny Sensorbox through an RS485 connection to each item. RS485 is a form of communications network that operates utilising two pairs of twisted conductors which allow for both data transmission as well as the transmission of a reference voltage [19].

The Sunny Webbox will be the heart of the communications system. The Webbox will then be connected to each inverter in a daisy-chain arrangement (Ie. Webbox to Sensorbox, Sensorbox to Sunny Island, Sunny Island to Windy Boy, Windy Boy to
Sunny Boy). The Webbox then connects to the PC to feed data to the Sunny Data Control software for analysis. It is to be noted, however, that the SMA monitoring equipment is only capable of an average sample rate of one sample per second, which is not fast enough to meet the requirements of this monitoring system. A one second sample interval does not allow a fast enough measurement to capture any transient waveforms of the line cycle frequency in the AC network.

In figure 11 above, the purple text boxes indicate the parameters that are to be measured. Some of these parameters are available through the SMA equipment present in the system. However, some require a specific monitoring system.

The new monitoring system has been designed to utilise the SMA monitoring system to its full extent, as well as incorporate as many of the existing systems’ sensors and monitoring equipment as possible. Due to time constraints, the system has been designed with provisions for all future sensor requirements with a vision to implementing a monitoring system that can monitor and display system parameters in real time. The existing environmental monitoring system listed in table 3 of appendix B remains unchanged and will be integrated into the future system in a method that suits the chosen software package.

The SMA inverters connected through the RS485 network in conjunction with SMA’s Sunny Data Control software allows a significant number of parameters to be monitored without utilising third party equipment. Any parameters that an SMA inverter logs or observes for its own monitoring, control or safety purposes can be extracted and logged locally on a computer. SMA’s equipment and software packages operate on open-protocol software code, allowing a future student to write a custom built piece of software to extract all required data from the inverters and display these in real time on an appropriate software package such as LabVIEW.

Table 4 in appendix D has been divided into the system’s constituent parts, namely the solar system, wind system, battery bank/Sunny Island system, diesel generator and the load/AC bus. The table specifies the exact location of monitoring parameters in the system with respect to the monitoring system design displayed in figure 21. Table 4 in appendix D displays all parameters that require monitoring and what equipment is
required to measure these parameters, such as the appropriate isolators, sensors or oscilloscope probes. It is to be noted that the SMA equipment cannot monitor or display voltage and current waveforms, hence, provisions for isolation amplifiers are required to provide a suitable location for connecting an oscilloscope’s current probes. These isolation amplifiers, however, then double as a point at which suitable voltage and current sensors can be connected in the future. This duplication is unavoidable. The SMA equipment is also not capable of monitoring such parameters as the operational power factor of each inverter and the load power factor (and hence reactive power flow), the frequency of the wind turbine’s AC output, and the diesel generator’s output voltage, current and frequency.

**Solar system:**

The solar system is to be monitored on both the DC and AC side of the inverter. The intention is to be able to visualise the power converting aspects of the inverter such as the conversion of DC electricity into a pure AC sine wave, as well as the presence of a 100Hz ripple on the DC side of the inverter due to it being a single phase unit. The DC voltage and DC current can be measured through the inverter itself by utilising SMA’s Sunny Data Control (SDC) software, however, waveform measurements are not possible. Thus, a voltage isolation amplifier and a current isolation amplifier on the inverter’s DC side are specified in order to allow an oscilloscope’s voltage and current probes to be connected. However, the presence of these isolation amplifiers allows the possible connection of voltage and current sensors which are already present in the existing monitoring system (if required), thus, the future capabilities of the SMA equipment (following future development of the monitoring system) will determine the requirement for these sensors. The inverter’s DC voltage and current measurements can be extracted from the Sunny Boy inverter through the SDC software or alternatively a simple voltage divider and current shunt can be connected to the appropriate isolation amplifiers. The sensors in table 4 of appendix D have been sized to coincide with the largest expected measurement ranges.

The inverter’s AC RMS current output is measured through the SDC software. While its RMS output voltage can also be measured, this will be addressed in the ‘Load/AC Bus’ section below and thus has been eliminated from measurement in this section.
Voltage and current isolation amplifiers on the AC side of the inverter are present to allow the measurement of the inverter’s AC output waveforms. With the presence of an oscilloscope measuring these waveforms, a simple calculation can be utilised to determine the power factor of the inverter. However it is to be noted that the Sunny Boy inverter is not capable of reactive power support, thus the power factor will be unity.

The total number of isolation amplifiers required to achieve the above requirements is 3 (1 for voltage, 2 for current). Sensor requirements include a current probe and voltage probe. Optional sensors relating to future development by taking measurements directly from isolation amplifiers include a voltage divider and two 30A 75mV current shunts (i.e. A 0 – 75mV signal voltage represents 0 - 30A of current flowing).

**Wind system:**

The wind system is to be monitored on the AC and DC sides of the Windy Boy inverter, as well as the AC side (output) of the wind turbine.

Both wind turbines’ output to the wind turbine controllers cannot be measured by the inverters, thus, third party monitoring equipment is required. Turbine output frequency, RMS voltage, RMS current and the respective voltage and current waveforms require measurement. An isolation amplifier for the voltage is required which will allow the connection of the oscilloscope’s voltage probe as well as a suitable voltage divider. It is to be noted that detailed specifications of the turbines’ output voltages were available in the associated turbines’ user manuals. However, these manuals were in transit with the turbines at the time this monitoring system was designed. No data sheets were available on the internet. An isolation amplifier for the current is also required for the connection of a suitable current shunt to measure the RMS current and the oscilloscope’s current probe to allow viewing of the current waveform. Current specifications for the two wind turbines were also in the user manuals.

In order to observe the frequency of the wind turbine’s AC output as it relates to wind speed, a simple voltage sense wire (wrapped around one phase of each turbine’s
output) detects the frequency of the voltage. This output is then fed through a voltage isolation amplifier for measurement by the data acquisition card. If required, a simple calculation relating to the number of pole pairs in the generator can take this measurement one step further and calculate the wind turbine rotor’s speed in revolutions per minute. It is to be noted that these wind turbine output sensors must be duplicated in order to cater for the AC output of both turbines. Transferring sensors between the two turbines can be time consuming and leaves the monitoring system at greater risk to damage in the situation where sensors are connected incorrectly after a turbine changeover.

The turbine’s controller is effectively an AC to DC rectifier. Monitoring on the DC side of the turbine controller (i.e. the Windy Boy inverter’s DC input) will measure current and voltage magnitudes as well as their respective waveforms. Measurement of the controller’s DC and AC currents and voltages allow the controller’s efficiency to be determined, while the waveform measurements provide a tool for visualising the controller’s rectifying action. The turbine controller’s output is also the inverter’s input, thus, the wind turbine’s DC current and voltage can be measured utilising the SDC software. Once again, current and voltage isolation amplifiers on the DC side of the inverter are required to allow waveform measurements. This, however, allows provisions for the installation of third party voltage and current sensors in the future if required.

Measurement of the inverter’s AC output voltage will be addressed in the ‘Load/AC Bus’ section. The inverter’s AC RMS current output will be measured by the SDC software. Voltage and current isolation amplifiers exist on the AC side of the inverter to allow the inverter’s output waveforms to be measured. Through a simple calculation, these waveforms are also able to provide the inverter’s power factor. However it is to be noted that the Windy Boy inverter is not capable of reactive power support, thus the power factor will be unity.

The total number of isolation amplifiers required to achieve the above requirements is 6 (3 for voltage, 3 for current). Sensor requirements include a voltage sense wire, a voltage probe and a current probe. Optional sensors relating to future development by
taking measurements directly from isolation amplifiers include two voltage dividers and two current shunts.

**Battery/Sunny Island System:**

The Sunny Island inverter’s input and outputs require measurement in order to determine the conversion efficiency of the inverter, visualise the DC to AC power conversion process from battery bank to AC network, and to monitor any effects of this process, such as a 100Hz ripple existing on the DC side of a single phase inverter.

DC monitoring includes voltage and current isolation amplifiers which provide for oscilloscope connections to measure waveforms. DC voltage and current measurements are extracted from the inverter utilising the SDC software.

AC monitoring includes voltage and current isolation amplifiers to provide suitable oscilloscope connection points for waveform measurement. The Sunny Island inverter is the only inverter in the system which delivers reactive power. These measurements will also allow a calculation of the inverter’s power factor. The RMS current measurement is obtained through the SDC software. The RMS voltage is again addressed in the ‘Load/AC Bus’ section.

The total number of isolation amplifiers required to achieve the above requirements is 3 (1 for voltage, 2 for current). Sensor requirements include a voltage probe and a current probe. Optional sensors relating to future development by taking measurements directly from isolation amplifiers include a voltage divider and two current shunts.

**Diesel Generator:**

The diesel generator, while passing through the Sunny Island’s internal relay, is unable to have its operating parameters monitored by the Sunny Island. For this reason, third party monitoring has been used. A voltage and current isolation amplifier will be connected to the diesel generator’s output to allow for RMS voltage and current measurement as well as the voltage and current waveforms. Although the
generator is rated to generate at a power factor of 0.8, the waveform measurements allow confirmation of the diesel generator’s actual power factor.

A voltage divider capable of reading the diesel generator’s peak voltage ($240V_{\text{RMS}} = 339.4V_{\text{PEAK}}$) will be utilised to supply a voltage signal to the data acquisition card and a 60A 75mA current shunt which exists in the current monitoring system will be used to supply a current signal.

The total number of isolation amplifiers required to achieve the above requirements is 2 (1 for voltage, 1 for current). Sensor requirements include a voltage probe, a current probe, a suitably rated voltage divider and a 60A 75 mA current shunt.

**Load/AC Bus:**

The load measurements relate to many of the same parameters as the inverter outputs.

Both a voltage and current isolation amplifier are connected to view the waveforms of the load current and voltage. This will allow the power factor to be determined and thus allow an understanding of how the Sunny Island controls reactive power flows at varying voltage levels.

The load voltage can be determined by viewing the voltage of one of the inverters connected to the AC bus. As there is no significant impedance between the inverters and the load, the voltage at the inverter’s terminals represents a relatively accurate measurement of the load voltage.

The total real load current is able to be determined by summing the output of all AC coupled generators and inverters in the system. The outputs of the Sunny Boy inverter, Windy Boy inverter and Sunny Island inverter can be viewed by the SDC software and manually added together, and by using the inverter voltage, it can be used to determine the load’s real power consumption. If the diesel generator is running, its output can also be extracted from the third party monitoring equipment and added to the sum of the inverter outputs to determine the total load consumption. It is
anticipated that the future LabVIEW program will be designed to do this automatically.

The frequency of the AC bus can be determined by referring to the output frequency of any of the system’s AC coupled inverters, which is displayed on the SDC’s display screen. As they will all be synchronised, the output frequency of any AC coupled inverter will be representative of the AC bus.

The total number of isolation amplifiers required to achieve the above requirements is 2 (1 for voltage, 1 for current). Sensor requirements include a voltage probe and a current probe. Optional sensors relating to future development by taking measurements directly from isolation amplifiers include a voltage divider and a current shunt.

**Overall data collection and Future Development:**

A suitable field point unit and data acquisition card is to be utilised which will sample at a sufficient rate to capture transients on the AC network. Hence, each channel is to be sampled at a rate of greater than 100 times every 20ms (1 cycle at 50Hz) as a minimum in order to capture any transients. Sample times are thus to be greater than 200μs. It is to be noted that sample times of 200μs will only capture the line cycles. This card will take readings from third party sensors located in the system such as the wind turbine output, the diesel generator and the load.

A suitable LabVIEW program will need to be designed in order to automate and consolidate all measurements within the system. This will include merging the measurements taken from the SMA inverters through the RS485 network with the measurements taken from third party monitoring equipment. This will then allow the simple development of a display screen that allows the system’s operational parameters to be easily visualised in a central location as well as removing much of the effort involved with manual calculations, such as determining the total load demand.
By consolidating the data from each sensor into one screen, the various operational characteristics of the inverters can be visualised in real time. For example, a large load can be switched on to visualise the operation of the droop control algorithm in the Sunny Island inverter, and then suddenly switched off at a time of high renewable energy input to visualise the operation of the Sunny Island’s frequency shift power control. Varying the combination of loads that are operating can also allow the visualisation of changing power factor as loads such as motors are started. With the development of a suitably designed LabVIEW program, the possibilities are vast and will allow a more complex display of system performance for more advanced educational purposes.
6.0 Concluding Statements and Future Work:

A number of unavoidable delays have prevented the system from being commissioned. However, this report has attempted to present information of a suitable detail for another student to pursue the project to completion.

The objectives of the project have been achieved, namely:

- The operational characteristics/principles of operation of the Sunny Island inverter have been investigated and documented.
- The existing energy system was assessed and equipment documented. This allowed the selection of suitable components for the proposed Sunny Island system.
- An electrical design exercise was conducted in order to display how the Sunny Island inverter will be incorporated into the existing system. The results are displayed in Appendix A.
- A suitable monitoring system has been proposed.

A number of items relating to future development have been listed below. These form a guide for the following student to have an understanding of what parts of the project are outstanding, as well as providing ideas for future improvement, development and expansion of the Sunny Island system following commissioning. These items include:

**Incorporation of an electric start diesel generator:** The current system’s manual generator is to be converted to an electric start unit that is interactive with the Sunny Island inverter. The WTD unit’s suitability should be explored.

**Commissioning of the system** – The renewable energy system is to be installed and commissioned by a suitably qualified party.

**Monitoring system development** – A design for the proposed monitoring system and a proposal for its implementation has been developed. This will allow a future student to install and commission both the SMA and third party monitoring system.

**Monitoring system expansion** – The SMA data collection and third party monitoring equipment is to be merged into a single LabVIEW program. This will allow data
collection to be consolidated in a single location and all values display on a simple screen which allow a more simple conceptualisation and demonstration of frequency shift power control and other operational characteristics of the system.

**Development of training material** – The system is quite a complex one with a wide range of capabilities. A training manual with a number of training exercises and detailed instructions on how to carry out tests should be created to display the various principles which the system is designed to demonstrate, including:

- Droop control and frequency shift power control
- Real power/frequency control and voltage/reactive power control
- Load sharing between the inverters and between the inverters and the diesel generator when it is operational
- Battery charging regimes
- Displaying power conversion equipment in action – E.g. Wind turbine controllers rectifying the wind turbine’s wild-AC output into DC current, and the inverters rectifying DC output to AC output.
- Efficiency tests of inverters and other power converters within the system
- The system’s performance and operation under overload conditions.
- The system’s performance when the battery bank is completely discharged (i.e. do the inverters supply the load and charge the batteries, or do they perform in a different way?)
- Develop islanding tests to monitor the behaviour of the AC-coupled generators.

**Incorporation of RISE’s system 1**: The new Sunny Island system will utilise RISE’s system 2 display unit as a base (refer to section 4.0 – ‘The Existing System, Proposed System and Associated Problems’). Adjacent to system 2 is system 1, a small-scale system based around a remote home scenario which consists of a 680W PV array, a 2.2kW inverter, 24VDC battery bank with 10kWh of storage and access to system 2’s diesel generator through two battery chargers. For educational purposes, a second Sunny Island inverter such as a 2.2kW Sunny Island 2224 could be implemented with the existing 24V battery bank and linked to the new Sunny Island 5048 inverter to display how the two inverters communicate and interact to control the system frequency and voltage. It is to be noted that Sunny Island inverters in parallel fall into a master/slave configuration. Load sharing and battery management regimes relating
to multi-inverter systems would also be possible with this arrangement, thus allowing for further technical analysis by power engineering students.

**Addition of further PV** – System 2’s new PV system has been designed with an array isolator that is rated to isolate a PV array that is double the size of the currently proposed 14 module array. Thus, the system can be effectively expanded in the future if required. This may be beneficial if the display is expanded to include the second Sunny Island inverter or extra loads.

**Fuel Cell addition** – A novel system expansion could include the use of RISE’s fuel cell setup. The system is currently unused. However, the system could be integrated with SMA’s recently developed Hydro Boy inverter. This would allow users to be educated about the process of the hydrolysis of water to create hydrogen and the further conversion of this hydrogen into useable electricity. The hydrogen could also be presented as another form of energy storage when produced with excess electricity from the wind turbines and solar array. The Hydro Boy inverter also allows for waste heat recovery from the fuel cell, allowing the display system to have a small hot water storage tank which can display the benefits of heat recovery to the visiting public and display the system’s wide range of capabilities.
7.0 References:


8.0 Appendix A: Electrical Design

The system’s electrical design was completed in accordance with the relevant Australian Standards related to off-grid energy systems (renewable energy generation), grid-connected energy systems (inverters) and electrical wiring. The Western Power Technical Rules were also used to determine the suitability of the Sunny Island for grid connection.

Standards utilised include:

**AS5033:2005 “Installation of Photovoltaic Arrays”** – AS5033:2005 was used extensively in the reconfigured design of the PV array. It provided information and guidance in the selection of string sizes, electrical protection of the array and inverter, isolation requirements, array segmentation requirements and considerations of lightning protection.

**AS3008 “Electrical Installations – Selection of cables”** – AS3008 provided guidance in selecting the appropriate sized cables for each part of the system including the solar array’s and wind turbines’ DC connections, the AC inverters’ connections to the AC network, the battery bank’s connection to the Sunny Island inverter and the diesel generator’s connection to the Sunny Island inverter.

**AS3000 “Wiring Rules”** – Being a standalone system, AS3000 was referred to in order to ensure that the system can be grid-connected in the future with little modification should the Sunny Island inverter become AS4777 approved.

**AS4509 “Stand-alone Power Systems”** – AS4509 provided overall guidance in the system design in the areas of electrical protection, cable sizing, system configuration and safety aspects.

**AS4777 “Grid Connection of Energy Systems via Inverters”** – Due to the Sunny Island not being grid-connected, there was no great need for AS4777, however, as per AS3000 it was consulted in order to identify whether the Sunny Island was suitable for grid-connection in Western Australia. While technically it has the ability to
undergo testing and possibly receive accreditation, it has not yet been tested and certified in accordance with AS4777, thus not being allowed to grid-connect in Western Australia.

**AS3010 “Electrical Installations – Generating Sets”** – AS4509 provides some brief guidelines regarding the location of generator sets. However, AS3010 provides clear indications for the connection requirements of the diesel generator primarily in regards to isolation and overcurrent protection. Other items in the standard such as changeover switches and synchronisation are not required as this task is undertaken by the Sunny Island inverter.

The first step in the electrical design process involved determining the appropriate connection method for each renewable energy generator. The Sunny Island inverter and its associated battery bank forms the heart of the system. An SMA SI5048 was already purchased for this system, thus all designs would be based around this size of inverter and any generation sources and other equipment already present in the existing system. The only exception is the wind turbine which was replaced with two new units which will operate for both the training system and for testing purposes in conjunction with the National Small Wind Turbine Test Centre.

The initial electrical design involved the reconfiguration of the solar PV array and the selection of appropriate wind turbines, following which an appropriate inverter was chosen for both generation sources. The maximum voltage of the new array configuration was determined in accordance with the minimum expected temperature and the cell’s temperature coefficients.

AS5033 was followed in order to implement appropriate protection for the DC connection of both the Sunny Boy and Windy Boy inverters. AS4777 and AS3000 were used to select the appropriate protection devices for the AC side of all inverters including the Sunny Boy, Windy Boy and Sunny Island.

AS3008, AS3000 and AS4509.2 proved essential in selecting appropriately sized cables for the system. These standards provided sizing tables as well as suggested maximum voltage drop limits for cables and temperature derating factors.
Further comments on the design process are presented in the electrical design drawings below.

Calculations:

**PV System:**

Inverter: SMA Sunny Boy SB1100

\[
\begin{align*}
V_{\text{MPPT}} &= 139 – 320V \\
V_{\text{MPPT, min}} &\rightarrow \text{Apply 10% safety margin} = 139 \times 1.1V = 152.9V \\
V_{\text{MPPT, max}} &\rightarrow \text{Apply 5% safety margin} = 320 \times 0.95V = 304.0V \\
V_{\text{MPPT, inverter}} &= 152.9V – 304V
\end{align*}
\]

Determine module \( V_{\text{min}} \) which occurs at \( T_{\text{max}} = 75°C \)

\[
V_{\text{min}} = V_{\text{MPP}} - [\gamma(T_{\text{max}} - T_{\text{STC}})]
= 16.9 - [0.075(75-25)]
= 13.15V
\]

Determine module \( V_{\text{max}} \) which occurs \( @ T_{\text{min}} = 5°C \)

\[
V_{\text{min}} = V_{\text{O,STC}} - [\gamma(T_{\text{min}} - T_{\text{STC}})]
= 21 - [0.075(5-25)]
= 22.5V
\]

Therefore, allowing for 5% cable losses:

\[
V_{\text{min}} = 13.15 \times 0.95 = 12.4925V \\
V_{\text{max}} = 22.50 \times 0.95 = 21.3750V
\]

Thus:

Minimum modules required = \( \frac{152.9}{12.4925} \) = 12.23 = 13 modules in series

Maximum modules required = \( \frac{304}{21.375} \) = 14.22 = 14 modules in series.

The new array configuration will consist of a single string of 14 modules in series.

\[
\begin{align*}
T_{\text{STC}} &= \text{Module operating temperature under standard test conditions (25°C)} \\
T_{\text{max}} &= \text{Module’s highest expected operating temperature} \\
T_{\text{min}} &= \text{Module’s lowest expected operating temperature} \\
V_{\text{MPPT}} &= \text{Inverter’s maximum power point tracking range} \\
V_{\text{MPPT, min}} &= \text{Inverter’s lowest safety factor adjusted maximum power point value} \\
V_{\text{MPPT, max}} &= \text{Inverter’s highest safety factor adjusted maximum power point value} \\
V_{\text{MPPT, inverter}} &= \text{Inverter’s safety factor adjusted maximum power point tracking range} \\
V_{\text{min}} &= \text{Minimum module voltage occurring at } T_{\text{max}} \\
V_{\text{max}} &= \text{Maximum module voltage occurring at } T_{\text{min}} \\
V_{\text{MPP}} &= \text{Module’s maximum power point voltage} \\
V_{\text{O,STC}} &= \text{Module’s open-circuit voltage at standard test conditions.} \\
\gamma &= \text{Module’s } V_{\text{O,STC}} \text{ temperature coefficient}
\end{align*}
\]
General design and installation notes:
- Ensure that all cables are sized in accordance with the relevant Australian Standards.
- Polarised DC circuit breakers are not to be used.
- Inverters are to cease operation if a DC earth fault is detected.
- Refer AS4509.2 for cable sizing – Appendix C.
- Cable sizing to be re-confirmed prior to installation.

Figure 13: Electrical design part 1 - Overall system layout.
Figure 14: Electrical design part 2 – Photovoltaic system design.
Figure 15: Electrical design part 3 – Wind system design.
Figure 16: Electrical design part 4 – Diesel generator system design.
Figure 17: Electrical design part 5 – Battery bank and Sunny Island system design.
### 9.0 Appendix B: Existing monitoring system:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Expected Range</th>
<th>Sensor combination</th>
<th>Sensor 1 Raw Output</th>
<th>Range of Raw Output</th>
<th>Sensor 1 Calibration Factor</th>
<th>Display Meter Analogue or Comment</th>
<th>Input range to Sensor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery Voltage (DC bus Voltage)</td>
<td>S2V\textsubscript{batt}</td>
<td>V</td>
<td>0-60V</td>
<td>Voltage Divider &amp; Isolation Amp</td>
<td>Voltage Divider 60V to 30V 2x47kohm voltage</td>
<td>0-30V</td>
<td>V x 2</td>
<td>40-60V (existing, before divider)</td>
<td>-40 to 40V</td>
</tr>
<tr>
<td>Battery Current (+/-)</td>
<td>S2A\textsubscript{batt}</td>
<td>A</td>
<td>-100 to +100A</td>
<td>Current Shunt &amp; Isolation Amp</td>
<td>Voltage Divider 60V to 30V 2x47kohm shunt voltage</td>
<td>-75 to 75mV mV / 0.375</td>
<td>-120/0/120 75mV 243-01CG 45mV/0/45mV (Off 200/75mV shunt)</td>
<td>-100mV to 100mV</td>
<td></td>
</tr>
<tr>
<td>PV Voltage - Before controller</td>
<td>S2V\textsubscript{pv}</td>
<td>V</td>
<td>0 - 70V</td>
<td>Voltage Divider &amp; Isolation Amp</td>
<td>Voltage Divider 60V to 30V 2x47kohm voltage</td>
<td>0-30V</td>
<td>V x 2</td>
<td>243-01VG - 40-70V scaled</td>
<td>-40 to 40V</td>
</tr>
<tr>
<td>PV Current - Before controller</td>
<td>S2A\textsubscript{pv}</td>
<td>A</td>
<td>0-20A</td>
<td>Current Shunt &amp; Isolation Amp</td>
<td>Current Shunt &amp; Isolation Amp</td>
<td>30A 75mV shunt voltage</td>
<td>0-75mV mV x 0.4</td>
<td>0-30A 243-01 AG</td>
<td>100mV Current output from sensor 1 and 240V AC voltage</td>
</tr>
<tr>
<td>Load Power AC</td>
<td>S2P\textsubscript{L}</td>
<td>W</td>
<td>0-3kW plus surge</td>
<td>Current transformer into Power transducer</td>
<td>Current Transformer</td>
<td>current 0-5A</td>
<td>A x 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gen Set Power AC</td>
<td>S2P\textsubscript{GS}</td>
<td>W</td>
<td>0-5kW plus surge</td>
<td>Current transformer into Power transducer</td>
<td>Current Transformer</td>
<td>current 0-5A</td>
<td>A x 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverter DC current</td>
<td>S2DCA\textsubscript{INV}</td>
<td>A</td>
<td>-100 to +100A</td>
<td>Current Shunt &amp; Isolation Amp</td>
<td>Voltage Divider 60V to 30V 2x47kohm shunt voltage</td>
<td>-75 to 75mV mV / 0.375</td>
<td>-120/0/120 75mV 243-01CG 45mV/0/45mV (Off 200/75mV shunt)</td>
<td>-100mV to 100mV</td>
<td></td>
</tr>
</tbody>
</table>
### Wind Turbine DC current

**Parameter:** Wind Turbine DC current  
**Symbol:** S2WT  
**Unit:** A  
**Expected Range:** 0 - 60A  
**Sensor combination:** Current Shunt & Isolation Amp  
**Shunt:** 60A 75mV  
**Voltage:** 0-75mV mV x 0.8  
**Sensor 1 Calibration Factor:** 0-60A 243-01 AG  
**Range of Raw Output 1:** -100mV to 100mV  

### Dump Load DC current

**Parameter:** Dump Load DC current  
**Symbol:** S2AOL  
**Unit:** A  
**Expected Range:** 0-60A  
**Sensor combination:** Current Shunt & Isolation Amp  
**Shunt:** 60A 75mV  
**Voltage:** 0-75mV mV x 0.8  
**Sensor 1 Calibration Factor:** 0-60A 243-01 AG  
**Range of Raw Output 1:** -100mV to 100mV  

### PV DC current (after controller)

**Parameter:** PV DC current (after controller)  
**Symbol:** S2APV(conf)  
**Unit:** A  
**Expected Range:** 0-30A  
**Sensor combination:** Current Shunt & Isolation Amp  
**Shunt:** 30A 75mV  
**Voltage:** 0-75mV mV x 0.4  
**Sensor 1 Calibration Factor:** 0-30A 243-01 AG  
**Range of Raw Output 1:** -100mV to 100mV  

### Wind Turbine RPM

**Parameter:** Wind Turbine RPM  
**Symbol:** S2RPMW  
**Unit:** RPM  
**Expected Range:** 150-900 RPM  
**Sensor combination:** Voltage sense wire from one phase of WT to freq to Voltage Iso Amp  
**Voltage sense wire from 1 phase of WT:** 22.5 - 135 Hz Hz x 60/9  
**Sensor 1 Calibration Factor:** RPM = 60 * Hz/Number of pole pairs (9)  
**Range of Raw Output 1:** 0 - 500Hz

---

**Table 2: Existing monitoring system sensors (electrical) [20]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Expected Range</th>
<th>Sensor combination</th>
<th>Sensor 1</th>
<th>Raw Output 1</th>
<th>Range of Raw Output 1</th>
<th>Sensor 1 Calibration Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Meteorological Data</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Irradiance (POA)</td>
<td>$G_i$</td>
<td>W.m$^{-2}$</td>
<td>0-1500 W.m$^{-2}$</td>
<td>pyranometer</td>
<td>K&amp;Z SP Lite</td>
<td>voltage</td>
<td>0-150mV</td>
<td>mV x 13.69863</td>
</tr>
<tr>
<td>Total Irradiance (Horizontal)</td>
<td>$G_H$</td>
<td>W.m$^{-2}$</td>
<td>0-1500 W.m$^{-2}$</td>
<td>pyranometer</td>
<td>K&amp;Z SP Lite</td>
<td>voltage</td>
<td>0-150mV</td>
<td>mV x 12.987</td>
</tr>
<tr>
<td>Relative humidity</td>
<td></td>
<td>%</td>
<td>0 – 100%</td>
<td>Humitter</td>
<td>Vaisala 50U/Y/YX</td>
<td>voltage</td>
<td>0 – 1V</td>
<td>V x 10</td>
</tr>
<tr>
<td>Atmospheric Pressure</td>
<td></td>
<td>MPa</td>
<td>15 – 115kPA</td>
<td>Barometer</td>
<td>NRG #BP20</td>
<td>voltage</td>
<td>0 – 5V</td>
<td>(V x 21.79) + 10.55 (typical)</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td></td>
<td>°C</td>
<td>0 - 45°C 360°</td>
<td>Temp transducer</td>
<td>Analog Devices AD592</td>
<td>current</td>
<td>-25 - 105°C</td>
<td></td>
</tr>
<tr>
<td>Wind Direction (18m)</td>
<td></td>
<td>°</td>
<td>continuous 360°</td>
<td>Wind vane</td>
<td>NRG #200P</td>
<td>voltage</td>
<td>0 – $V_{input}$</td>
<td>360x($V$/ $V_{input}$)</td>
</tr>
<tr>
<td>Wind Direction (30m)</td>
<td></td>
<td>°</td>
<td>continuous 360°</td>
<td>Wind vane</td>
<td>NRG #200P</td>
<td>voltage</td>
<td>0 – $V_{input}$</td>
<td>360x($V$/ $V_{input}$)</td>
</tr>
<tr>
<td>Wind Speed (18m)</td>
<td></td>
<td>m s$^{-1}$</td>
<td>1-96 m s$^{-1}$</td>
<td>Anemometer</td>
<td>NRG #40</td>
<td>frequency</td>
<td>0 – 125Hz</td>
<td>(fx0.765)+.35</td>
</tr>
<tr>
<td>Wind Speed (30m)</td>
<td></td>
<td>m s$^{-1}$</td>
<td>1-96 m s$^{-1}$</td>
<td>Anemometer</td>
<td>NRG #40</td>
<td>frequency</td>
<td>0 – 125Hz</td>
<td>(fx0.765)+.35</td>
</tr>
</tbody>
</table>

**Table 3: Existing monitoring system sensors (environmental) [20]**
Sensor types and monitoring system technology:

Isolation amplifier:

An isolation amplifier is an electronic component which mimics the operation of a handheld voltmeter by maintaining an isolation barrier between its input and output terminals – In doing so, there is no continuous path for any current to flow to ground [21]. By maintaining this electrical isolation, sensors and the data-acquisition system as a whole remains protected. The amplifier can also be used to boost low-amplitude signals when required.

Voltage divider:

A voltage divider is a circuit which scales a large system voltage down to a magnitude which is able to be measured by a data-acquisition system. Further information about the operation of a voltage divider is available in reference [22].

Current shunt:

A current shunt is a resistor with a small resistance value that is connected in series with the load. As the resistance is a known value, the voltage drop across this resistor can then be measured to determine the current flowing in the circuit by utilising Ohm’s law. As the current increases, the voltage drop measured by the data acquisition system will also increase.

Current transformer:

Figure 18: Diagram of a current transformer. Adapted from [23].
A current transformer is a measuring device which scales large currents down to a value which can be measured by a data acquisition system. The current being transmitted through the line to be monitored (primary coil) induces a magnetic field in the toroidal core. A winding around the toroid forms the secondary coil of the transformer which registers a signal current that is proportional to the number of turns in the secondary coil.

**Power transducer:**

The power transducer unit operates by converting the input current and input voltage measurements into a DC output signal which is proportional to the amount of power flowing in the circuit.

**Existing system measurements:**

**Battery voltage/DC bus voltage (V):** The battery voltage is measured by utilising a voltage divider and isolation amplifier; the voltage divider circuit consists of two 47 kΩ resistors in series. The expected battery voltage range of 0 – 60V is scaled to an output of 0 – 30V through the voltage divider circuit. This represents a factor of 2. Displayed on analogue meter.

**Battery charge/discharge current ie. ± (A):** The battery current is measured by utilising a current shunt and isolation amplifier. The current shunt is able to measure 0A - 200A which is represented by a signal voltage of 0mV – 75mV. Due do this, every 1A variation in current causes the signal voltage to vary by 0.375mV. The current flows to and from the battery are to be in the order of ±0 – 100A; this value is to be expected given the low voltage nature of the system (48V). It must also be noted that the expected current range is both positive and negative, allowing for both the inverter’s current draw from the battery as well as the inverter’s battery charging current to be measured. This will be represented by a positive or negative signal voltage based on the inverter’s state at the time (charge or discharge). Displayed on analogue meter.
**PV voltage – before controller (V):** The PV array is expected to have a voltage output range of 0 – 60/70V which is scaled down to 0 – 30V through an identical voltage divider circuit as the battery/DC bus voltage sensor, thus representing a scaling factor of 2. This voltage is measured prior to the PV array’s charge controller. Displayed on analogue meter.

**PV current – before controller (A):** The PV array current is expected to be in the order of 0 – 20A which is measured by a current shunt and isolation amplifier in the same way as the battery bank currents are measured. Having a maximum reading value of 30A at 75mV signal voltage, the current shunt will display a signal voltage increase of 2.5mV for every 1A increase in PV current. The current is measured prior to the PV array’s charge controller to avoid the influence of efficiency decreases on the measured value. Displayed on analogue meter.

**AC Load power (W):** The load power is measured by a Crompton M553 30A/5A current transformer. The load power is expected to range between 0 – 3kW (plus an allowance for surge currents due to motor starting, etc). Based on the current flowing, the current transformer outputs a signal current of 0 – 5A. The current transformer has a turns ratio of 30:5 (6:1), thus the RMS of the signal current is multiplied by 6 to determine the current flowing to the load. This is multiplied by the inverter’s output voltage (240V) to determine the load’s power consumption.

**Generator AC power (W):** The generators output power is measured by using the same equipment and equipment configuration as the AC load power, thus, current transformer’s output current signal is multiplied by a factor of 6 to determine the generator’s output current. This current is multiplied by its output voltage (240V) to determine the power output of the generator.

**Inverter DC current (A):** The inverter’s DC current (inverter input) measurement is taken from the battery charge/discharge current measurement. When the current is positive, it represents a discharge from the battery bank, thus the inverter’s DC current is equal to the +(0 – 100A) reading of the battery charge/discharge current measurement. Displayed on analogue meter.
**Wind turbine DC current (A):** The current wind turbine’s output current is measured utilising a similar sensor setup as the battery charge/discharge current. It is measured by using a 60A/75mV shunt to measure the wind turbine’s expected 0 – 60A output current. The current shunt will produce a signal voltage between 0 – 75mV which represents the shunt’s 0 – 60A input current range. This indicates that for every 1A increase in current, the signal voltage will increase by 1.25mV – Alternatively, it can be represented that for every 1mV increase in signal voltage, the wind turbine’s current output has increased by 0.8A. Displayed on analogue meter.

**Wind turbine dump load DC current (A):** The current wind turbine dump load’s output current is measured utilising an identical setup to the wind turbine’s output current. Displayed on analogue meter.

**PV DC current – after controller (A):** The PV array’s current after the controller is measured in an identical fashion to the DC current before the controller, ie. By utilising a 30A/75mA current shunt and isolation amplifier.

**Wind turbine RPM (rpm):** The wind turbine’s RPM is measured by using a voltage sense wire that is wrapped around one phase of the wind turbine’s output cables. It senses the frequency of the wind turbine’s output. Variations in wind speed cause variations in output frequency which can be converted into RPM. By taking the frequency output of the wind turbine and dividing it by the number of pole pairs in the wind turbine’s generator (9 pairs in total for the existing wind turbine), a value of wind turbine rotor revolutions per second can be obtained. This value can be multiplied by 60 to determine the wind turbine rotor’s rotational speed in revolutions per minute.

**Meteorological data recorded:**

**Plane of array solar (POA) Radiation (W m⁻²):** The plane of array radiation is measured by a pyranometer which is mounted at the same angle as the PV array. The pyranometer outputs a voltage which is proportional to the solar radiation detected by the pyranometer. The equation given under the column heading ‘Sensor 1 Calibration
Factor’ in table 3 (above) shows the relationship between the signal voltage and the solar irradiance.

**Horizontal solar radiation (W m⁻²):** The horizontal solar radiation is measured by a pyranometer which is mounted parallel to the horizon. As above, the pyranometer generates a voltage output signal.

**Relative humidity (%):** The relative humidity is measured by a “humitter” which is a sensor that measures both humidity using a hygrometer, and ambient temperature using a thermocouple. The ambient temperature function is not used in this instance as this is measured by a separate sensor. The humidity reading (0 – 100% relative humidity) is proportional to the sensor’s voltage signal (0 – 1V). [24].

**Atmospheric pressure (MPa):** The atmospheric pressure is measured with a barometer which outputs a voltage signal that is related to the barometric pressure by a function listed in the ‘Sensor 1 Calibration Factor’ column in table 3 (above). [25].

**Ambient Temperature (°C):** Refer to data sheet [26].

**Wind Direction @ 30m and 18m (°):** Wind direction is measured by a wind vane. The wind vane is effectively a potentiometer where the direction of the wind/wind vane causes resistance to vary, in turn causing a variation in the output voltage signal. The wind vane requires excitation by an external voltage source which then becomes the $V_{\text{input}}$ (reference voltage); the output signal voltage, divided by the input/excitation voltage, multiplied by 360° will provide the current wind direction. [27].

**Wind Speed @ 30m and 18m (m s⁻¹):** Wind speed is measured using an anemometer. It operates with similar principles to a wind turbine where the anemometer cups form the rotor that undergoes rotational motion due to the wind. This rotor drives a magnet which forms the generator assembly. The output thus becomes a sine wave whose frequency is proportional to wind speed. The function relating the anemometer signal to the wind speed is: Wind Speed = [(f x 0.765) + 0.35]. [28].
Appendix C: Screenshot of sample Sunny Portal and Sunny Data Control screens:

Figure 19: Sunny Portal display screen [18].
The above figure shows a sample screen shot of the Sunny Data Control’s display screen. The system is a generically generated display system.

Figure 20: Sunny Data Control display screen [29].
11.0 Appendix D: Proposed monitoring system

Figure 21: Proposed monitoring system parameters
### SOLAR SYSTEM

<table>
<thead>
<tr>
<th>Measurement Required</th>
<th>Measurement location</th>
<th>Measurement Type</th>
<th>Unit</th>
<th>Instrument</th>
<th>Expected range</th>
<th>Notes</th>
<th>Suitable Sensor</th>
<th>Existing?</th>
<th>Additional Equipment</th>
<th>Existing?</th>
<th>Direct from Inverter?</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_dC PV Rms</td>
<td>Inverter - DC side</td>
<td>Voltage</td>
<td>V</td>
<td>V divider and isolation amp</td>
<td>0 - 315V</td>
<td>Vmax @ 5C</td>
<td>Voltage divider</td>
<td>No</td>
<td>Isolation amp</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>I_dC (t)</td>
<td>Inverter - DC side</td>
<td>Current</td>
<td>A</td>
<td>Current shunt and isolation amp</td>
<td>-</td>
<td>0 - 5A</td>
<td>Isc of string</td>
<td>No</td>
<td>Same Iso Amp as $V_{dC PV Rms}$</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>I_dC PV Rms</td>
<td>Inverter - AC side</td>
<td>Current</td>
<td>A</td>
<td>Current shunt and isolation amp</td>
<td>-</td>
<td>0 - 5.6A</td>
<td>Imax of inverter</td>
<td>No</td>
<td>Same Iso Amp as $I_{dC PV Rms}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>I_dC PV (t)</td>
<td>Inverter - AC side</td>
<td>Waveform</td>
<td>-</td>
<td>Oscilloscope through an isolation amp</td>
<td>-</td>
<td>-</td>
<td>Current probe</td>
<td>No</td>
<td>Same Iso Amp as $I_{dC PV Rms}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Power factor</td>
<td>Inverter - AC side</td>
<td>Value Number</td>
<td></td>
<td>Oscilloscope/Calculation</td>
<td>-1 to 1</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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</table>

### WIND SYSTEM

#### Wind Turbine 1 and 2

<table>
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<th>Parameter</th>
<th>Measurement location</th>
<th>Measurement Type</th>
<th>Unit</th>
<th>Instrument</th>
<th>Expected range</th>
<th>Notes</th>
<th>Suitable Sensor</th>
<th>Existing?</th>
<th>Additional Equipment</th>
<th>Existing?</th>
<th>Direct from Inverter?</th>
</tr>
</thead>
<tbody>
<tr>
<td>V AC Wind turbine Rms</td>
<td>Wind turbine - AC side</td>
<td>Voltage</td>
<td>V</td>
<td>V divider and isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage divider</td>
<td>TBA</td>
<td>Yes</td>
<td>TBA</td>
<td>No</td>
</tr>
<tr>
<td>I AC (t)</td>
<td>Wind turbine - AC side</td>
<td>Current</td>
<td>A</td>
<td>Current shunt and isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $V_{AC Wind Rms}$</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>I AC PV Rms</td>
<td>Wind turbine - AC side</td>
<td>Current</td>
<td>A</td>
<td>Current shunt and isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $I_{AC PV Rms}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Frequency</td>
<td>Wind turbine - AC side</td>
<td>Value Integer</td>
<td></td>
<td>Voltage sense wire and isolation amp</td>
<td>0 - 500 Hz</td>
<td>Taken from Mehul's table</td>
<td>Yes</td>
<td>Isolation amplifier</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>I AC PV (t)</td>
<td>Inverter - DC side</td>
<td>Voltage</td>
<td>V</td>
<td>V divider and isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $V_{AC PV Rms}$</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>I AC PV Rms</td>
<td>Inverter - DC side</td>
<td>Current</td>
<td>A</td>
<td>Current shunt and isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $I_{AC PV Rms}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>I AC PV (t)</td>
<td>Inverter - AC side</td>
<td>Waveform</td>
<td>-</td>
<td>Oscilloscope through an isolation amp</td>
<td>-</td>
<td>-</td>
<td>Current probe</td>
<td>No</td>
<td>Same Iso Amp as $I_{AC PV Rms}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Power factor</td>
<td>Inverter - AC side</td>
<td>Value Number</td>
<td></td>
<td>Oscilloscope/Calculation</td>
<td>-1 to 1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No</td>
</tr>
</tbody>
</table>

Note: Wind turbine - AC side components require duplication to cater for both turbines.

### BATTERY / SUNNY ISLAND SYSTEM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement location</th>
<th>Measurement Type</th>
<th>Unit</th>
<th>Instrument</th>
<th>Expected range</th>
<th>Notes</th>
<th>Suitable Sensor</th>
<th>Existing?</th>
<th>Additional Equipment</th>
<th>Existing?</th>
<th>Direct from Inverter?</th>
</tr>
</thead>
<tbody>
<tr>
<td>V DC SL Rms</td>
<td>Inverter - DC side</td>
<td>Voltage</td>
<td>V</td>
<td>Voltage divider and isolation amp</td>
<td>0 - 60V</td>
<td>-</td>
<td>Voltage divider</td>
<td>Isolation amp</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>I DC (t)</td>
<td>Inverter - DC side</td>
<td>Waveform</td>
<td>-</td>
<td>Oscilloscope through an isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $V_{DC SL Rms}$</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>I DC SL Rms</td>
<td>Inverter - DC side</td>
<td>Current</td>
<td>A</td>
<td>Current shunt and isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $I_{DC SL Rms}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>I DC SL (t)</td>
<td>Inverter - DC side</td>
<td>Waveform</td>
<td>-</td>
<td>Oscilloscope through an isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $I_{DC SL Rms}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>I DC SL Rms</td>
<td>Inverter - AC side</td>
<td>Current</td>
<td>A</td>
<td>Current shunt and isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $I_{DC SL Rms}$</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>I DC SL (t)</td>
<td>Inverter - AC side</td>
<td>Waveform</td>
<td>-</td>
<td>Oscilloscope through an isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $I_{DC SL Rms}$</td>
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<tr>
<td>Power factor</td>
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<td>Value Number</td>
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<td>Oscilloscope/Calculation</td>
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### DIESEL GENERATOR

<table>
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<th>Measurement location</th>
<th>Measurement Type</th>
<th>Unit</th>
<th>Instrument</th>
<th>Expected range</th>
<th>Notes</th>
<th>Suitable Sensor</th>
<th>Existing?</th>
<th>Additional Equipment</th>
<th>Existing?</th>
<th>Direct from Inverter?</th>
</tr>
</thead>
<tbody>
<tr>
<td>V AC Diesel Rms</td>
<td>Output terminals</td>
<td>Voltage</td>
<td>V</td>
<td>V divider and isolation amp</td>
<td>0 - 339V</td>
<td>Vrms of 240V</td>
<td>Voltage divider</td>
<td>No</td>
<td>Isolation amp</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>I AC Diesel (t)</td>
<td>Output terminals</td>
<td>Current</td>
<td>A</td>
<td>Current shunt and isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $V_{AC Diesel Rms}$</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>I AC Diesel Rms</td>
<td>Output terminals</td>
<td>Current</td>
<td>A</td>
<td>Current shunt and isolation amp</td>
<td>0 - 21A</td>
<td>-</td>
<td>Assume PF = 1; 5kW @240V</td>
<td>No</td>
<td>Same Iso Amp as $I_{AC Diesel Rms}$</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>I AC Diesel (t)</td>
<td>Output terminals</td>
<td>Waveform</td>
<td>-</td>
<td>Oscilloscope through an isolation amp</td>
<td>-</td>
<td>-</td>
<td>Voltage probe</td>
<td>No</td>
<td>Same Iso Amp as $I_{AC Diesel Rms}$</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Power factor</td>
<td>Output terminals</td>
<td>Value Number</td>
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<td>Oscilloscope/Calculation</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>No</td>
</tr>
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</table>

**Notes:**
- Existing? and Notes columns may contain additional information specific to each measurement type.
- Direct from Inverter? column will indicate if the measurement is directly from the inverter itself.
<table>
<thead>
<tr>
<th>LOAD / AC BUS</th>
<th>At AC bus</th>
<th>Voltage</th>
<th>V divider and isolation amp</th>
<th>0 - 339v</th>
<th>Vrms of 240V</th>
<th>Voltage divider</th>
<th>隔离器</th>
<th>TBA</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{AC\text{-}bus, RMS} )</td>
<td>At AC bus</td>
<td>Current</td>
<td>A Current shunt and isolation amp</td>
<td>0 - 21.7A surge</td>
<td>Imax of inverter + surge</td>
<td>30A 75mV shunt</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Frequency</td>
<td>At AC bus</td>
<td>Value</td>
<td>Integer Extract from Sunny Island inverter</td>
<td>0 - 60Hz</td>
<td>Need &gt;50Hz to capture FSPC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power factor</td>
<td>At AC bus</td>
<td>Value</td>
<td>Number Oscilloscope/Calculation</td>
<td>-1 to 1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4: Proposed monitoring system parameter detail
Academic Supervisor endorsement pro forma:

I am satisfied with the progress of this thesis project and that the attached report is an accurate reflection of the work undertaken.

Signed: ________________________________

Date: _________________________________