CONTROL OF A HYBRID ENERGY SYSTEM

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Control of a Hybrid Energy System

By

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Abstract

Renewable energy systems today are becoming more popular due to the rise in fuel costs and the demand for energy both small and large scale. Many systems use one source of renewable energy such as wind or solar, and many control systems are designed to deal with only one source. Wind and solar can be combined to make a hybrid energy system. This allows for energy production almost all the time. For example, during the night solar systems have to rely on battery backup or diesel generation, but if a wind turbine is added to the system, power from the wind can be harnessed during the night and on cloudy days, and the solar can add to the wind or replace the turbine when there is no wind or a heavy load. For a hybrid (wind-solar) system to work effectively there has to be a control system. Combinations of single purpose controllers, such as a wind controller, solar controller and battery charger, are hard and complicated to integrate together. They require a lot of wire, space and increase the probability of failure of the system with one controller may work against the other. Some available controllers have solar added to a wind controller, but they can only handle a small amount of solar power with simple control and have no monitoring.

The main aim of this research was to determine a more effective way to combine and control multiple renewable energy sources. The methodology was to study prior art to determine how the problem was to be approached and what improvements are required to achieve the research task. This thesis focuses on small wind and small solar (less than

2500 watts), and the most effective way to control and combine these energy sources in an effective and efficient way.

This research introduces a new design to combine wind and solar together in a single controller called the Autonomous Renewable Control System – ARCS, to overcome different technical issues from industry and simplify renewable power. The controller takes a priority approach of power from wind first, then from solar. A system monitor was added to track performance of the system and to log historic data along with safety systems such as alarms and breakers. Included in this research is historical data produced from the test system such as power outputs, energy savings and environmental savings and other useful data. The data showed an increase power output from the wind turbine, combined power with the solar power and environmental savings. The ARCS showed improved control, simpler installation and operation, and effective hybrid energy management. This research provides the framework to expand on the design for larger systems and different control schemes.

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Confidentiality of Work

Technical details of the ARCS, such as circuit diagrams and code, are omitted from this thesis. This is due to the product commercialization, intellectual property ownership, and the patent submittal of the ARCS technology to the US Patent Office. Michael Snow developed the bases of the ARCS technology with input from the acknowledged persons at the beginning of this document.

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List of Abbreviations and Symbols

ARCS – Autonomous Renewable Control System
LDC – Load Diversion Controller
ADRC – Active Disturbances Rejection Control

List of Acronyms

FET – Field Effect Transistor
MOSFET – Metal Oxide Semiconductor Field Effect Transistor
LED – Light Emitting Diode
LCD – Liquid Crystal Display
IGBT - Insulated Gate Bipolar Transistor

Chapter 1

1.0 Introduction

This research was planned to determine a more effective way to combine and control multiple renewable energy sources. The methodology was to study the prior art to determine how the problem should be approached and what improvements are required to achieve the research task. This thesis focuses on small wind and small solar of less than 2500 watts combined total power, and the most effective way to control and combine these energy sources in and effective and efficient way. The research performed in this thesis was used to develop a product for WES Power Technology Inc., a renewable energy company specializing in hybrid energy management; therefore the intellectual property is owned by WES Power. Due to the nature of the research, some details are excluded, such as the programming code and detailed circuit diagrams due to confidentiality and trade secrets owned by WES Power Technology Inc.

This research has been presented at the 2005 Newfoundland Electrical and Computer Engineering Conference (NECEC) and at various WES Power Company events.

1.1 Background

A hybrid energy system comprises of power generation from multiple energy sources such as wind turbines, photovoltaics, batteries, fuel cells, micro hydro, and/or grid intertie.

With the increasing demand for clean energy power sources, renewable energy is becoming a more common part of everyday life. There are five major motivators to renewable power adoption:

1. There is a growing energy shortage problem incurring unreliable power in developed nations and the constant threat of rolling blackouts (Mosaddeq, 2003).

2. It is cost prohibitive or functionally impossible to distribute power to remote rural areas and under-developed nations.

3. The Kyoto Protocol is an agreement where industrialized countries will collectively reduce their greenhouse gases by 5% compared to 1990 in five years from 2008 – 2012 (United Nations, 1998).

4. The rising costs associated with fossil fuels are driving energy alternatives for power production (Chea, 2006).

5. The increasing amount of energy subsidies and incentives to adopt "cleaner" energy alternatives, particularly for wind and solar sources, is encouraging consumer investment, therefore reducing the capital cost of system installations.

While the result is a significant global trend and interest in wind/solar energy adoption, there remain significant technical hurdles to overcome and innovation is required to further increase consumer adoption. "Technology developmental needs: hybrid systems, controls, lightning/corrosion, meters (low cost prepaid), resource data, and integrators/package systems." (Nelson, 2002) This means there is a lot of work to be done to make renewable power a reliable source of power.

There are three major functional or technical barriers for renewable energy (NRCan, 2005):

1. These energy sources have high variability (for example a windy/cloudy day versus a calm/sunny day) for generating power and therefore require intelligent "control" that manages fluctuations and inherent variability problems.

2. Wind and solar system technology requires many different components (e.g. turbine, inverter, battery bank, switches, controllers, breakers) that also have inherent integration problems, which can cause inadvertent system shutdowns and is a major deterrent for adoption.

3. "Hybrid systems have a 65% or more failure rate, with failures due to components failing, poor maintenance, ..." (Nelson, 2002) Further research need to be done to increase reliability.

Consequently, these problems are driving the need for a solution in the form of intelligent "control". Research is needed to develop advanced and innovative functional solutions to control multiple renewable energy sources effectively, efficiently, and more reliably.

1.2 Current State of Development

Below is a summary of several wind and solar controllers from various manufacturers with a description of their operation and control. There are very few control solutions available for hybrid energy systems with multiple sources of power generation.

Southwest Wind Power

a. AIR-X Internal Controller

Figure 1: AIR -X Controller (Alternative Energy Store, 2006a)

The Air-X controller is built into the Air-X wind turbine from Southwest Wind Power. The turbine is rated at 400 watts. The AIR-X's charge controller periodically stops charging, reads the battery voltage, compares it to the voltage setting and if the battery is charged, it completely shuts off all current going to the battery. This function is performed within a few milliseconds. The closer the battery is to reaching its full state of charge, the more often the AIR-X's circuit repeats this action. This means any size battery bank from 25 to 25,000 amp hours or higher can be charged safely. When the battery has reached its charged state, the AIR-X turbine will slow to an almost complete stop. Only when the battery has dropped below its voltage set point will the turbine start-up and resume charging (Alternative Energy Store, 2006a)

This controller is for maintaining the charge of batteries using a wind turbine. The Air-X has the following drawbacks:

- It is specific to a single type of wind turbine
- It is not intended for use with other power sources such as other wind turbines, solar panels, or any type of conventional power.
- Its only function is to keep the batteries charged, and it has no intelligence on board to watch the operation of the turbine and batteries in case of a problem.

b. The EZ-Wire 120/1600 - For Whisper 100 & 200 Wind Turbines

Figure 2: EZ-Wire 120/1600 (Alternative Energy Store, 2006b)

The EZ120/1600 is a rectifier and bulk charge regulator for the Whisper 100 and Whisper 200 wind turbines. A selector switch on the front cover sets the regulation set point, and the scale is in volts/ cell for example for a 24V system: 2.40 Volts/Cell x 12 cells in a 24V bank = 28.8V regulation setting, and so on. When the control circuit decides that the batteries are charged according to the set point, the Light Emitting Diode (LED) indicator light comes on as the circuit signals a Field Effect Transistor (FET) switch assembly that serves as a relay to divert power to the external, resistive dump load (Southwest Windpower, 2006).

The turbine, the solar input to the EZ (if there is any), and the battery bank itself is all diverted to dump load during regulation. The controller has to be set higher than any other charge controllers that are on the same battery bank lest it try and suck whatever other charge sources the system has when it regulates. The dump load is rated at 1600 W. The turbine will peak at about 1200 W, which allows for only about 400 W of solar that can be wired through the unit without using an alternative solar controller. It is discouraged to use the "solar" option on the EZ120 as there is quite a variety of superior, three-stage solar controllers out there, and the EZ120 is a simple bulk charger (Southwest Windpower, 2006)

The EZ Controller allows for battery charge control and dump loading. It also allows for connection of solar panels. But it has the following drawbacks:

- It is specific to a single type of wind turbine
- Solar inputs very limited in power – up to 400W or 3-4 solar panels.
- Very limited LED display shows when power is diverted in charging, no information on turbine power or battery

c. The EZ-Wire 200 - For Whisper 500 Wind Turbines

Figure 3: EZ - Wire 200 (Alternative Energy Store, 2006c)

The EZ – Wire 200 is similar to the EZ – Wire 120 except it is built for the Whisper 500 a 5kW wind turbine. This Controller includes a diversion load, small solar hook-up and LED Display of system voltage (Southwest Wind Power, 2006b)

The EZ Controller allows for battery charge control and dump loading and solar hook-up. It has the following drawbacks:

- It is specific to a single type of wind turbine
- Small amount of solar capability
- Very limited LED display shows when power is diverted in charging

2) **Solar Converters Inc.**

a. **Wind Turbine Dump Load Controller**

Figure 4: Solar Converters' Controller (Alternative Energy Store, 2006d)

This unit uses a taper PWM control to ensure battery overload protection and to always supply a load to the wind turbine (Alternative Energy Store, 2006d).

This controller is for keeping a load on a wind turbine in case of excess power when the batteries are fully charged. It has the following drawbacks:

- Need to supply resistive load.
- Only controls wind turbine.
- It has no indicators or LCD/LED on board to watch the operation of the turbine or batteries in case of a problem.

3) Bergey Windpower

a. PowerCenter Controller

Figure 5: Power Center (Bergey Windpower, 2006)

PowerCenter controller is for the Bergey XL.1 and was the first microprocessor equipped small wind turbine controller. This controller provides quiet turbine operation in high winds, and has something called "Slow Mode". When the batteries reach float voltage the rotor speed is reduced to provide only the current necessary to maintain the battery voltage at float. The wind turbine will not free wheel and blades will not flutter. If the turbine free wheels (no load), the wind turbine will spin out of control and may damage itself or others if the blades fail. If the load increases the PowerCenter will sense the need for more current and it will allow the turbine to spin faster to provide that current (up to 120 W). Slow Mode works whether you have a dump load or not. On a windy day, with the batteries full, the rotor speed can be controlled by turning lights in your house on or off. A built in brake button brings the wind turbine to a stop and a wattmeter function with each LED lit indicates 100 Watts of output. The controller has a dump load capacity of 60 Amps using PWM control to maintain battery voltage within tight limits. A built-in polarity checker for the wind turbine and PV inputs prevents reverse hook up (Bergey Windpower, 2006).

At low wind speeds, performance is greatly enhanced by a low-end-boost circuit that optimally loads the wind turbine down to wind speeds as low as 2.5 m/s (Bergey Windpower, 2006).

This controller allows for battery charge control with a dump load option, built in brake button and power level display through LEDs. It allows for connection of solar panels as well. It has the following drawbacks:

- It is specific to a single type of wind turbine
- Small solar power input.

4) **University of New Brunswick**

Currently, researchers at the University of New Brunswick are focusing on the development of innovative power electronic converters and advanced control strategies for variable speed wind turbine systems. Two of the several development platforms include the single-phase 10kW/240V grid-connected IGBT inverter used on a Bergey Excel 10 kW wind turbine in Charlottetown, Prince Edward Island, and the three-phase 100kW/380V grid-connected IGBT inverter used on a Lagawey LW18 80kW wind turbine in North Cape, PEI. The 10 kW system was developed for residential power generation, and the 100 kW system was developed for wind-diesel applications in remote communities. The R&D work has expanded to include distributed generation packages powered by micro hydro units and micro turbines, in addition to wind turbines. (Wind Energy Conversion Systems, Chang, UNB)

5) Sunny Island

The Sunny Island from SMA is a Battery management inverter used to tie together hybrid energy sources such as wind, solar, hydro, and/or generators. It is used to manage the power from the various sources. It requires a Windy Boy controller in order to add wind and a Sunny Boy controller to add solar on the AC side. The Sunny Island has generator management, battery deep discharge management, and grid control. This controller requires several controllers to act as a hybrid system. (SMA Technologies)

6) Other types of controllers

Yang (2004) discusses the control of Hybrid Energy Systems using Fuzzy logic Control. Fuzzy Logic work around a set of rules, as the number of variables increase, the number of rules grows exponentially. This is how a system is designed traditionally. Yang (2004) uses Hierarchical Fuzzy Control (HFC) which allows the reduction in the number of rules, simplifying the process. The system used in the model is 5 - 15kW wind turbines, and a 15kW solar array. This system is much larger (5 – 15kW) than the research model to be used. A larger system with multiple wind turbines and a large solar array will have a different set of rules for control (Yang, 2004).

1.2.1 Control of Hybrid Wind-Solar Power Systems

Valenciaga (2005) describes supervisor control for a wind turbine, solar array, batteries, and an AC load. The idea is to maintain power to the load as well as charge the batteries. The system includes several DC-DC converters, one for wind and one for solar along with a rectifier circuit for the wind turbine. This hooks into an AC load. This system operates in three modes. Mode 1 is where the wind turbine is capable of supplying the entire load. When this is no longer the case Mode 2 is entered where the solar also contributes to the load. The final Mode 3 is when the wind, solar, and battery supply the entire load until it cannot supply enough power any more (Valenciaga, 2005).

Sebastian (2002) discusses hybrid wind-diesel systems using a distributed control system on a controller area network or CAN Bus. The CAN bus is used as an automotive industry standard. It is cheap, reliable and robust and simple to use. The idea is to use a CAN bus control system to control a hybrid wind-diesel. Sebastian (2002) describes three modes; wind only, wind-diesel, and diesel only and various ways to control them. The system has to maintain the load while minimizing the diesel fuel consumed. The system also has dump load and a storage system to maximize the energy and maintain the load.

Zhang (2004) uses ADRC (Active Disturbances Rejection Control) technology using a new type of nonlinear function and was applied in an extended state observer and nonlinear state observer and nonlinear state error feedback controller. A comparison of standard PID control and ADRC control was researched and shows that the ADRC control settles down much faster, and had a much better response then PID control. This method was applied to renewable energy by applying it to an inverter that had a constant controlled voltage.

1.3 Controller Issues

The current technology has many benefits for the control of small wind turbines and solar panels. As indicated from this research, there are several problems that still exist.

- Most of the controllers only work with one specific kind of wind turbine or solar array;
- There is little integration of both wind and solar power in the one controller. Most controllers do not control solar, or can only control small amounts of solar;
- There is a lack of system monitoring and power management;
- There is no sophisticated system monitoring system detail such as power, current, and voltage readouts;
- There is no data logging of history of performance of the system to track problems;
- There is no computer connection to view or store data from system;

- There is little intelligent management of multiple power sources such as wind turbine, solar array, inverter, and battery (full system management).

1.4 Impact of Technology

This research helps to simplify the use of hybrid renewable energy systems by combining a controller for wind and solar, batteries and inverter, with data acquisition. This will allow a greater acceptance of renewable power, more reliable integrated hybrid systems, and greater use of power from hybrid control. Data acquisition, logging and history will provide critical performance information, and can provide greenhouse gas estimates, and cost savings. This will provide useful information on the impact a hybrid system will have on energy consumption.

Chapter 2

2.0 System Sizing Using HOMER

The program HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation (DG) applications. HOMER's optimization and sensitivity analysis algorithms allow the evaluation of the economic and technical feasibility of a large number of technology options. This accounts for variations in technology costs and energy resource availability (HOMER - Analysis of micro power system options, 2006).

2.1 Test System Setup

The setup of the program allows various renewable and/or conventional sources, weather or resource data, and various constraints to be considered. The analysis performed is based on the test system used in the research. The test system is outlined below with technical data included.

2.1.1 Southwest Windpower Whisper 200 (H80)

The Whisper 200, as shown in figure 6, used in the test system is wired for 48V DC. The Whisper 200 is designed to operate in a site with low to medium wind speed averages of 8 mph, 3.6 m/s, and greater. The Whisper 200 provides 200+ kWh per month, 6.8 kWh per day, in a 5.36 m/s average wind (http://www.windenergy.com/whisper_200.htm).

Figure 8 shows the factory power curve for the Whisper 200. In the Results section a comparison of the factory power curve and the power curve measured during the research is given. The graph shows that the maximum power from the wind turbine occurs at a wind speed of approximately 13.5 m/s to produce 1000w of power. The power output begins to decrease at wind speeds greater than 13.5 m/s. This is because the wind turbine has a furling mechanism that spills the wind at high wind speeds to help control the speed. This is done using a spring on a pivot. When the force from the wind exceeds the spring force, the blades tilt to one side reducing the speed of the rotor as shown in figure 7.

Figure 6: Whisper 200

Figure 7: Whisper 200 Tilting

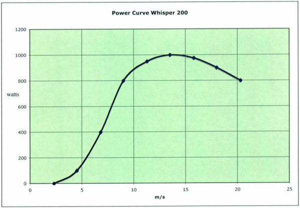

Figure 8: Power Curve

2.1.2 Evergreen 110 Solar Panels (Two)

Two Evergreen Solar panels, as shown in figure 9, were used in the test system with a rating of 110W each at 24V DC. They were wired in series to provide 48V DC for the test system. They were added to the 48V DC wind turbine to make a hybrid system. These panels use String Ribbon technology. This technology combines the best attributes of conventional crystalline silicon and thin films. It achieves the reliability (less breakdown from UV and heat), stability, and high efficiency, of crystalline silicon (Evergreen Solar, 2007).

Figure 9: Evergreen Solar Panels

2.1.3 Xantrex SW5548 Inverter/Charger

The Xantrex inverter that was used in the test system was a 5.5kW true sine wave inverter. It had an input of 48V DC to match the system and 120V AC at 60 Hz frequency output. This was used to power any AC loads though an AC breaker panel to see how the system responded to various loads as shown in figure 10.

Figure 10: Inverter and AC Panel

2.1.4 Mastercraft Deep Cycle Nautilus Battery

The batteries, as shown in figure 11, were used in the test system. They are a cost effective deep cycle battery alternative to expensive Trojan 6V batteries. The Trojan batteries are expensive due to the large metal plates to provide a large amp/hour rating. A large amp/hour rating is better because it allows a much larger draw of current without discharging the battery as fast, providing a much larger capacity. A total of four 12V DC Deep Cycle batteries were used in series to provide 48V DC. They are flooded lead acid with a 100-amp/hr rating. They are not ideal for large loads due to their small amp/hour capacity and ability to draw a smaller current, but are sufficient for testing purposes.

Figure 11: Lead Acid Batteries

2.1.5 Davis Vantage Pro Weather Station

This weather station was used to collect information on the wind speed and the solar intensity to allow comparison of system output vs. weather conditions. If the wind turbine is not outputting power in high wind, it means there is a system problem. Likewise if there is a high solar intensity and there is no power from the solar panels, they may not be working correctly.

2.1.6 Load

The system load consists of a 1500w heater and a 3 speed fan that is cycled manually according to system conditions. This gave a total maximum load of approximately 1600w. At high wind speeds and sunny conditions the system can maintain the load and slowly charge the batteries. The system is capable of providing up to 5.5kW of power, but only for a short time where most of the energy will come from the batteries.

2.2 Analysis (sensitivity analysis)

The program HOMER, developed by the US National Renewable Energy Laboratory (NREL), can be used in assisting the sizing of a renewable energy system to be sure it is capable of maintaining the load, while looking at the economics of installing a system. It helps to optimize the system for the least amount of money. It was used in this case to ensure that the chosen system was capable of providing results with the available resources and the test load. This test load was several lights plugged into the AC panel, to provide a load of 150 watts or 1 kWh/day.

2.2.1 System architecture

The system architecture used in the research is outlined in figure 12 and table 1, which is the same as described above.

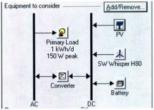

Figure 12: Block Diagram

Table 1: System Architecture

PV Array:	0.22	kW (2 x 110w)
Wind turbine:	1	SW Whisper H80
Battery:	4	Nautilus Deep Cycle
Inverter:	5.5	kW
Rectifier:	4.13	kW

2.2.2 Cost Summary

The cost summary, shown in table 2, shows the total net present cost of the system for the year 2007 by taking the total annualized cost divided by capital recovery factor, interest rate, and project lifetime (Tom Lambert, 2004). The cost works out to be $1.575 kWh which is high compared to the rate in Newfoundland of 8.644 cents kWh. This cost is high due to the small size of the system, but the cost is not a large issue if no electricity is available and fuel is hard to transport on site, such as for a remote cabin. The levelized cost of energy is the cost per kWh from the systems production. This number should be as low as possible for a system providing power to a home or business, but is not important for this research. Table 3 shows the breakdown of the individual cost of each of the components. This would be very important for use in production and system sizing, but is not as critical in this research.

Table 2: Cost Summary

Total net present cost:	7,911	$
Levelized cost of energy:	1.575	$/kWh

Table 3: Cost Detail

Component	Initial Capital	Annualized Capital	Annualized Replacement	Annual O&M	Annual Fuel	Total Annualized
	($)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
PV Array	1,000	73	0	40	0	113
SW Whisper H80	2,150	156	0	5	0	161
Battery	360	26	23	24	0	73
Converter	3,000	218	0	10	0	228
Totals	**6,510**	**473**	**23**	**79**	**0**	**575**

The cost details include operation and maintenance plus the cost of operation per year over the life of the system. The batteries only have a 10-year span, therefore will have to be replaced twice before the systems expected life runs out in 30 years with proper maintenance. This is accounted for in the annualized replacement cost.

2.2.3 Annual Electricity Energy Production

The production of energy is shown in table 4 and figure 13 and shows the breakdown of production in kilowatt-hours per year (kWh/year) based on Environment Canada weather data for St. John's, Newfoundland and the percentage of contribution to the total energy produced in the system. From the resources, wind and sun, most of the power is produced by the wind turbine.

Table 4: Energy Production

Component	Production (kWh/yr)	Fraction
PV array	328	13%
Wind turbine	2,266	87%
Total	2,594	100%

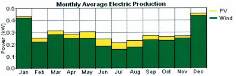

Figure 13: Average Energy Production

2.2.4 Annual Electrical Energy Consumption

The following tables 5 and 6 shows the power consumed in a year and the percentage of power that is sold back to the grid. It shows that 100% of the total load is serviced by renewable power where there is no grid present in the test system to sell back to or draw from.

Table 5: Load

Load	Consumption (kWh/yr)	Fraction
AC primary load	365	100%
Total	365	100%

Table 6: Renewable Fraction

Variable	Value	Units
Renewable fraction:	1.000	
Excess electricity:	2,196	kWh/yr
Unmet load:	0	kWh/yr
Capacity shortage:	0	kWh/yr

2.2.5 Photovoltaic

The photovoltaic power production is shown in table 7 and figure 14. Figure 15 shows one year of weather data used from Environment Canada. Table 7 shows that the solar penetration is 90%, which is the average power output of the PV array divided by the average primary load (Tom Lambert, 2004). Only 17.05% of the solar array total capacity is utilized. This indicates that the solar array would be more effective in a sunnier place. From figure 14, it shows that the maximum power is produced during the summer months.

Table 7: PV Production

Variable	Value	Units
Average output:	0.900	kWh/d
Minimum output:	0.0001003	kW
Maximum output:	0.420	kW
Solar penetration:	90.0	%
Capacity factor:	17.05	%
Hours of operation:	4,601	hr/yr

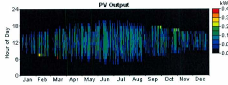

Figure 14: PV Production

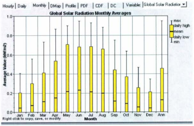

Figure 15: Solar Data (HOMER)

2.2.6 DC Wind Turbine: SW Whisper H80

The DC wind turbine in table 8 and figure 16 shows how much power the turbine produces. Figure 17 shows the wind speed for a full year used in the analysis from

Environment Canada, St. John's, Newfoundland. The table shows that the wind penetration is 621%, and only 25.8% of the turbines total output is utilized. Wind penetration is the average power output of the wind turbine divided by the average primary load (Tom Lambert, 2004). This indicates that the turbine could produce much more power if the tower was higher or the average wind speed was higher. Figure 16 shows that the maximum power produced was mainly in the winter months from Nov – Jan shown in orange.

Table 8: Wind Production

Variable	Value	Units
Total capacity:	1.002	kW
Average output:	0.259	kW
Minimum output:	0.000	kW
Maximum output:	1.002	kW
Wind penetration:	621	%
Capacity factor:	25.8	%
Hours of operation:	6,911	hr/yr

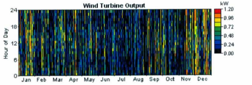

Figure 16: Wind Production

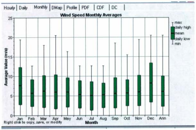

Figure 17: Wind Data (HOMER)

2.2.7 Battery

The following data shown in figures 18, 19, and 20 shows that the battery is nearly always 100% charged. During the winter months it shows that the battery will become less than 100% charged. This is due to larger loads turned on during testing. This case shows that the battery maintains maximum life expectancy due to its minimal use and minimal cycling. The battery bank autonomy is the ratio of the battery bank size to the electric load (Tom Lambert, 2004). It will take 69.1 hours to drain with the system load.

Table 9: Battery

Variable	Value	Units
Battery throughput	80	kWh/yr
Battery life	10.00	yr
Battery autonomy	69.1	hours

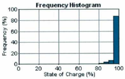

Figure 18: State of Charge

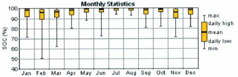

Figure 19: Monthly State of Charge

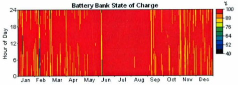

Figure 20: State of Charge During Day

Chapter 3

3.0 Methodology of Controller Design

This chapter deals with the methodology used in the design of a control system for a Hybrid Renewable Energy System.

3.1 Introduction

Clean energy systems are being encouraged all over the world as a way to reduce pollution and still produce the energy needed to run peoples' day-to-day lives. These systems are not easy to install, control or monitor and require constant attention, maintenance and care, to work correctly.

This research explores the development of a power management system for land-based power systems that entails renewable energy sources as a main or supplemental power source. To increase system performance and reliability several things should be considered. Active monitoring of the power sources in the system and control of their use in an efficient manner was explored allowing for an easy way to control and keep track of the power consumption and availability from the system.

3.2 Background

The renewable energy market for small wind and solar systems (less than 10kW) has only been picking up momentum in the last 10 years. The number of companies that deal in small wind turbines, solar panels or other renewable sources is also increasing. The equipment provided by these companies usually provide some way to make the power from the source useable, but offers little automated control, and no easy way to integrate a multi source system into a full system.

The aim of the technology being developed in this research was to provide a practical and reliable solution towards the existing problem of integrating renewable energy sources together with other power sources. The key was to address the industry need for more reliable, economical and functional power control systems that minimizes the need for components, and effectively manage the variability associated with renewable energy sources such as solar panels and small wind turbines. This research considered the following key features in the design:

- **Reliability**: The project aims to increase renewable energy system reliability of operation and therefore significantly encourage adoption of renewable energy technologies. This will be done by effective control topography, careful monitoring of system components that will link directly with the control of the system.
- **Efficiency**: The project aims for maximum efficiency using intelligent control of the renewable power sources that will increase their power output capturing and harnessing as much power generation as possible.

- **Integration**: The project aims to integrate multiple power sources and thereby increase the transition to renewable power by allowing a stage approach. For example, the purchase of a wind turbine can be installed first, than later; a solar array can be added easily without any controller changes or upgrades.
- **Component Number**: It aims to reduce the need for multiple electrical devices into one (1) smart power system device.
- **Component Size**: The project reduces the number of components being used allowing for more space from up to 6 devices down to 1 device.
- **Scaling**: The project aims to be easily scalable from a small system to larger systems and then to a grid tie system into a utility power grid.
- **Flexibility**: The project aims for the use of multiple components from various manufacturers, such as different turbines or solar panels.
- **Quality**: The project will offer high-quality and reliability by using good design practices and component selection.
- **Functionality**: The project aims to automatically control various devices in a power system to increase reliability and added convenience. It should also be able to flag or alert of any system problems.
- **Convenience**: The system aims to be self managing with little intervention required.

This kind of renewable system is becoming more popular, especially in remote locations, as well as on boats, as oil prices rise. This project aims to solve the need for a power management control system to provide control and monitoring of small scale hybrid energy systems.

3.3 Technical Background and Strategy

In order for the power management system to operate efficiently, it requires the regulation of the power that is monitored to be controlled efficiently. The project focuses on:

- The design, implementation, and installation of a group of power regulation circuitry to regulate the power coming from the various sources.
- Design of motherboard for data acquisition, components, and PCB design.
- Design of data acquisition sensor pack to measure current and voltage.
- Design of circuit protection and external component protection.
- Software for both the hardware control and a PC computer interface.
- Case design and packaging.

The first step was the design of a power regulation circuit (or Load Diversion Controller – LDC) for incoming renewable sources including a wind turbine and solar array. It aims to be capable of wind turbines up to 1.5kW peak and 1kW of solar. It aims to regulate the voltage of the incoming power to a set value to match the system power to optimally charge lead acid batteries, extending their life. The circuit aims to be designed to handle high and varying currents and voltages, as well as be interactive with the microprocessor, consuming as little power as possible. The LDR is a self-contained unit that is not dependent on any other components such as the data acquisition unit, but interacts passively.

The second step was to design the motherboard for data acquisition and control of the solar array. The motherboard consists of a microprocessor, Analog to Digital converter, onboard memory, and digital output with driver circuit, relay controller, and data acquisition circuit. This is used to acquire data from the system such as voltage and current, control the relays, and send data to the computer and LCD, and store data.

The third step was the design of the actual sensor pack that is used to measure the voltage and current. The voltage is measured with a simple voltage divider circuit using 1% resistors and the current is measured with Hall Effect sensors. The sensor pack will measure each source, the wind turbine, the solar array, inverter, and batteries on a PCB board capable of handling the current.

The fourth step was the design of various safety features to be included to increase the safety, increases reliability, and protects the components and devices of the system from short circuit, over current and voltage transients. Protection for the batteries, inverter, wind turbine, and solar array should be considered. The wind turbine can not have a breaker or fuse because if it were to trip, the wind turbine can over speed and damage itself.

The fifth step was the packaging and case. This is not critical for this research, but was considered to ensure the unit is safe to operate and easy to install and test. This can be built from steel or aluminum.

3.4 General Design Overview

Figure 21 shows the design overview of the controller, methodology, and general architecture of the project. Shown are the various blocks that will be considered in the design.

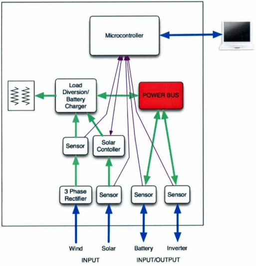

Figure 21: System Block Diagram

Figure 21 shows the main components are the microcontroller, which obtains information from the sensors and solar control. The Load Diversion/Battery Charger works independently of the microprocessor and controls the power from the wind turbine and diverts excess power to the dump load. All the sources are connected through the Power BUS both positive and negative, which routes the power to the correct location.

3.5 *Project Objectives*

This project contains a number of technical and strategic objectives as listed below.

3.5.1 Technical Objectives

The software portion of this project was done by a third party with assistance and guidance from the programmer where this is not the focus of this thesis as indicated in the software sections. Some assistance was obtained on Part 1 regulation design.

The primary technical objectives are as follows:

1) Regulator Design and Implementation:
    - Design of the regulation circuitry to allow more efficient charging of the batteries of a system (Some assistance was required);
    - Build and test the circuitry;
    - Tuning the circuit for best regulation.

2) AC Power Rectification:
    - Design of the AC power rectifier to DC for turbines with 3 phase power;
    - Implementation and installation of the design.

3) LCD/Keypad – Processor Integration:
    - Design and Implementation of processor integration into current motherboard;
    - LCD display and keypad research;
    - Integration of LCD/Keypad;

- Software for new processor for communications with LCD display, keypad and original processor (Third Party).

4) Memory Integration:
    - Memory chip integration into motherboard;
    - Programming to store/retrieve data (Third Party).

5) TCP/IP Communications and Graphical User Interface (GUI) (Third Party):
    - Programming TCP/IP into the processor for server setup;
    - Create GUI to communicate with controller;
    - Add graphs and displays to GUI, using communicated information from sensor readings and from memory - when that is completed;
    - Look into using GUI software to communicate over the internet to access remote locations (e.g. cabin (with internet) from home/work).

6) Case Design:
    - Design a case to house electronics, sensors, dump load, and safety breakers;
    - Layout design to ensure all components integrates correctly.

7) Assembly and Beta Prototyping:
    - Assembly of final design for testing.

8) Final Testing:
    - Eliminating bugs in hardware after integration;
    - Extensive hardware testing for flaws;
    - Extensive software testing for bugs; (Third Party Assistance)
    - Final assembly configurations.

3.5.2 Strategic Objectives

The following points were the strategic aims of the research:

- Improved performance of hybrid energy system;
- Quick easy setup;
- Safe operation of system;
- Ability to monitor system performance;
- Development of final prototype;
- Build several beta prototypes for testing in field;
- Achieve as many of the design criteria as possible:
    - 1500W of wind;
    - 1000W solar;
    - PWM lead acid charging;
    - System and performance monitoring;
    - Computer interface;
    - Alarms and safety.

Chapter 4

4.0 Implementation of the Hybrid Energy Controller

4.1 Overview Implementation of the Hybrid Energy Controller

The project was called the ARCS (**A**utonomous **R**enewable **C**ontrol **S**ystem). The ARCS project consists of several design blocks. The hardware consists of power electronics, microelectronics, software, and mechanical layout. The hardware has a total of five components. These consist of the Load Diversion Controller (LDC), the AC rectification circuit, motherboard for data acquisition, the sensor pack, and safety systems. The software component consists of both firmware on the hardware (microcontroller program), and software for the Windows® computer. The final component was the mechanical layout and packaging of the system. Figure 22 shows an overview of the design of the ARCS.

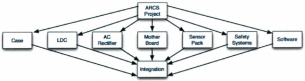

Figure 22: System Design Overview

4.1.1 Hardware (block diagram and photos)

The hardware consists of five main components, the LDC, AC Rectification, and Motherboard for Data Acquisition, Sensor pack, and safety systems.

4.1.2 Case

The case was designed for optimal cooling and ease of use. All connectors and switches were easy to access, and are laid out in logical order. This made the testing of the ARCS much easier due to the nature of the project. Figure 23 shows the case design and figure 24 the case layout. The case is made from rolled steel and powder coated white for durability and looks. The case is not an essential part of the research project and was the last thing to be implemented; however t was important part of the commercialization.

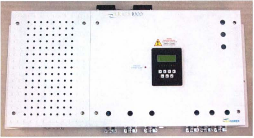

Figure 23: ARCS

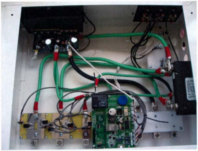

Figure 24: Case Layout

4.1.3 Load Diversion Controller (LDC) for Wind and Solar

The Load Diversion Controller was designed to properly charge the lead acid batteries and to control the wind turbine and solar array. The LDC uses the system voltage to be able to control the system. As the voltage approaches the optimal value for the system voltage, for example a 48 VDC system optimal charge voltage is 56.7 VDC for lead acid batteries; the system reduces the current going to the batteries and diverts the power to the resistive dump load (figure 25). This had to be done to control the speed and output of the wind turbine. If the turbine was to 'free wheel' with no load the turbine can over speed and exceed its rated no load power output and damage itself.

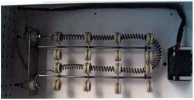

Figure 25: Dump Load

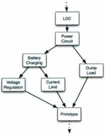

Figure 26: LDC Block Diagram

Figure 26 shows how the LDC design is put together. The power circuit retrieves power from the batteries to make the unit self-powering. It is able to take in a voltage from 60 – 12VDC to give a steady output of 24 VDC up to 2A. Using an on chip buck DC – DC converter 24 VDC is achieved. The DC – DC converter was used to power all the circuits in the ARCS, including the LDC, motherboard, and all support circuitry.

The battery charging uses a Pulse Width Modulation (PWM) method. PWM is an effective method for charging Lead Acid batteries. Using PWM is a newer method than 3 – stage (bulk, float and absorption) and 2 – stage charging (bulk and float). Figure 27 shows the completed circuit board. The PCB was made of four layers to allow the passage of up to 60A through the main power traces and a large heat sink is attached to the MOSFETS to allow for adequate cooling.

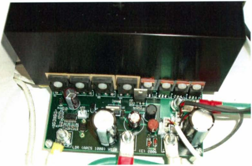

Figure 27: LDC Circuit

4.1.3.1 Tuning

The Load Diversion Regulator (LDR) is effectively a pulse width modulated switch. A resistor divider divides the voltage output from the wind turbine. A 2.5 V reference derived from the 5V REF voltage output on TL494 (U1) and another resistor divider.

These two voltages are fed into the error amplifier portion of U1 (1IN+, 1IN-, FEEDBACK). This amplifier is inverting and gain-limited to 100. Resistor and a capacitor dictate the PWM frequency and the prescribed values yield 10 kHz. Various frequencies where tried up to 50 kHz, but 10 kHz seemed to be the optimal from trial and error. Other frequencies would cause the system not to respond correctly and not be critically damped. The duty cycle of the switch output (C2 and E2 of U1) gradually increases as the wind turbine output voltage approaches 57.6V for the 48V system and 28.8V for the 24V system. These correspond to the recommended absorption voltages for charging lead-acid batteries.

The output of U1 is arranged in an emitter-follower configuration. When on, it drives the totem-pole driver and lights the dump LED via a current limiting resistor. The driver outputs roughly 10V to the MOSFETs, which in turn switches on the dump load. A diode protects the MOSFETs from any voltage kickbacks resulting from inductance in the dump load resistor. The transient voltage suppressor diode, filtering capacitor, and snubber circuit also guard against voltage spikes that may arise from switching. Diodes prevent backflow from the battery to the wind turbine.

The power circuitry portion of the LDR board uses the TL783 and the LM2592HVADJ parts. The TL783 (Q6), in conjunction with programming resistors R20 and R21, generates a fixed voltage of 12V which powers the LDR circuitry. The topology surrounding the LM2592HVADJ part (U2) is a standard buck converter with protection circuitry. Details can be found in the LM2592HVADJ datasheet.

4.1.4 AC Rectifier Circuit

The AC Rectifier circuit takes three phase-unregulated power from a wind turbine up to 1500 watts and converts it to an unregulated DC voltage. This is done by using a simple three phase full rectifier circuit as shown in figure 28 and the circuit in figure 29. The main challenge is to be sure there is adequate cooling of the diodes to prevent failure. A large black anodized aluminum heat sink was used to be sure of adequate cooling.

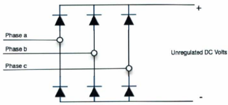

Figure 28: AC Rectifier Circuit

Figure 29: Rectifier Circuit

4.1.5 Motherboard Design

The motherboard design does all the processing of data from the sensor block. It is capable of measuring voltage, current, controlling relays, driving an LCD, user keypad, and storing data in memory.

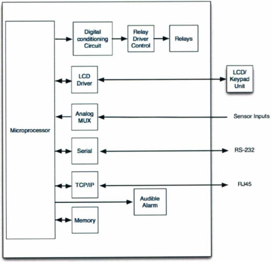

Figure 30: Motherboard Block Diagram

4.1.5.1 Microprocessor

The microprocessor on the motherboard was critical for operation of the ARCS. A microprocessor had to be selected that was able to perform many tasks simultaneously efficiently. It has to be small in size and consume very little power. The processor that has been selected remains confidential as a trade secret of WES Power Technology. The microprocessor is capable of analog inputs, and digital I/O. There are sufficient available lines to integrate LCD/Keypad, memory, TCP/IP, and other necessary circuitry to perform the data acquisition. The I/O signals from the microprocessor are 3.3 VDC in order to be energy efficient.

4.1.5.2 Digital Conditioning Circuit

The digital conditioning circuit was used to ensure that the logic high is 5 VDC and that logic low is 0 VDC. Without this circuit, there was not enough voltage on the output of the processor 3.3 VDC to ensure that a logic high signal is guaranteed. This circuit makes sure the signal is clean and noise free, and that there are no floating values.

4.1.5.3 Relay Driver Control

The relay driver ensures there was enough power to drive control relays. The control relays are used to switch large amounts of power, therefore a driver circuit is required to switch the relays because the microprocessor was not capable of driving the relay alone, only to provide a signal for switching the relay. The relays can require up to 1 amp of instantaneous power to switch the contacts of the relay. The circuit consists of a BJT transistor, some resistors and diodes to allow the correct voltage to switch the relay (12 VDC) using a 5-volt signal from the digital conditioning circuit by command from the microprocessor.

4.1.5.4 Relays

The ARCS system consists of up to two relays. Relay 1 was used to control the power that comes from the solar array. When the batteries are fully charged, and the system begins to "dump" the power to the dump load resistor, the solar array is disconnected to ensure the batteries are not over charged. When the solar arrays are connected, the LDC using PWM charging controls them. The rating on Relay 1 is 60A. Relay 2 is optional and is used to disconnect an inverter before the voltage drops below the minimum. If the voltage drops below the minimum for some inverters, the inverter shuts down, but does not re-engage when the voltage comes up. The relay allows the system to cut out the inverter before it shuts itself off, and re-engage the inverter when the voltage is sufficiently high. This relay was controlled in the same way as Relay 1, and can be rated at 100A or 200A depending on the inverter.

4.1.5.5 LCD Driver

The LCD driver was used to display information on the LCD to allow the user to view information and input information. This circuitry uses buffers for the signal to the LCD.

4.1.5.6 LCD/Keypad

This unit was a combined preassembled unit that has a LCD display 122 x 32 graphic display/keypad as shown in figure 31. This includes all the necessary hardware for interfacing.

Figure 31: LCD/Keypad

4.1.5.7 *Analog MUX*

The analog multiplexer that was chosen is the ADG408 8-bit MUX from Analog Devices. The ADG408 switches one of eight inputs to a common output as determined by the 3-bit binary address lines A0, A1, and A2. This allows conserving the use of lines on the microprocessor for other tasks and adding 8 analog inputs. The analog input range is from 0 – 10V, which is selected in sequence using the 3-bit binary address lines. This chip has low power consumption, high switching speed, and a low on resistance, making it ideal for this application.

4.1.5.8 *Serial*

The motherboard has a serial port to allow communications to a computer. It transmits the raw data to a communications program where the user can view. In order to add this component to the motherboard, support circuitry was added. The MAX232 chip is a driver/receiver chip used in communication interfaces. This is a low power chip and allows the easy integration of serial RS-232 to the motherboard.

4.1.5.9 TCP/IP

A very important feature that was added to the motherboard is TCP/IP connectivity. This allows the ARCS to connect to any intranet or Internet to transmit data to a Graphical User Interface (GUI) on a computer over a network from local or remote locations. This allowed a unique experience of bringing data from multiple renewable energy sources to your desktop.

4.1.5.10 Audible Alarm

A useful feature added to the ARCS project was the ability to alarm if something goes wrong. This made it easy for testing and provides a useful feature for future use. If a current exceeds a set value, a voltage was too low or too high, an audible alarm is triggered using a pizo electric speaker and a signal is transmitted to the LCD and GUI.

4.1.5.11 Memory

The ARCS has a total memory of 2MB, which allows up to 1 year of data storage. The memory used is SPI or Serial Protocol Interface, which allows multiple devices to be connected on the one interface using only a few data lines. Up to 16MB can be added for future expansion. The original design used an 8MB memory chip but it was decided to use only a 2MB chip instead due to the cost.

Chosen was the Atmel AT45DB161D, which is a 2.5-volt or 2.7-volt, serial-interface sequential access Flash memory ideally suited data-storage. The AT45DB161D supports RapidS serial interface for applications requiring very high speed operations. RapidS serial interface is SPI compatible for frequencies up to 66 MHz. Its 17,301,504 bits of memory are organized as 4,096 pages of 512 bytes or 528 bytes each. In addition to the main memory, the AT45DB161D also contains two SRAM buffers of 512/528 bytes each. The buffers allow the receiving of data while a page in the main Memory is being reprogrammed, as well as writing a continuous data stream. Unlike conventional Flash memories that are accessed randomly with multiple address lines and a parallel interface, the DataFlash uses a RapidS serial interface sequentially to access its data. The simple sequential access dramatically reduces active pin count, facilitates hardware layout, increases system reliability, minimizes switching noise, and reduces package size. The device has low-pin count, low-voltage and low-power consumption (Atmel, 2006).

4.1.5.12 Completed Motherboard Circuit

The motherboard consists of both surface-mount and through-hole components that was placed by hand and then verified and tested. Figure 32 show the completed PCB board.

Figure 32: Motherboard PCB

4.1.6 Sensor Pack

The sensor pack consists of current sensors, and voltage sensors. The current sensors used are ACS754-100-CB from Allegro.

The Allegro current sensor provides economical and precise solutions for current sensing. The device package allows for easy implementation. The sensor consists of a precision, low-offset linear Hall sensor circuit with a copper conduction path located near the die. Applied current flowing through this copper conduction path generates a magnetic field which is sensed by the integrated Hall IC and converted into a proportional voltage. Device accuracy is optimized through the close proximity of the magnetic signal to the Hall transducer. A precise, proportional voltage is provided by the low-offset, chopper stabilized BiCMOS Hall IC, which is programmed for accuracy at the factory. Figure 33 shows the completed current sensor pack PCB board.

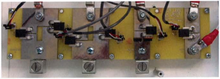

Figure 33: PCB Sensor Pack

The output of the device has a positive slope (>VCC / 2) when an increasing current flows through the primary copper conduction path, which is the path used for current sensing. The internal resistance of this conductive path is typically 100 $\mu\Omega$, providing low power loss. The thickness of the copper conductor allows survival of the device up to 5 times over current conditions. The terminals of the conductive path are electrically isolated from the sensor. This allows the sensor to be used in applications requiring electrical isolation without the use of opto-isolators or other costly isolation techniques. The device is fully calibrated from the factory. To increase the accuracy, a calibration program is run to detect any offset from the zero mark and compensate by an appropriate multiplier (Allegro, 2007).

The voltage sensor was a voltage attenuator achieved by using 1% resistor in a voltage divider to ensure the analog voltage does not exceed 10V. The analog input can only read a maximum of 10V.

4.1.7 Safety System

Safety in a renewable system was paramount for both testing and future use. Breakers have been added to protect against over current, and short circuits. There was a breaker on the battery/inverter rated for 125A at 60VDC, and 40A at 48VDC for the solar array as seen in figure 34. The solar array also has built in diodes to prevent back flow of current from the battery to the solar panels. This is included on the sensor PCB.

Figure 34: Breakers

There was an electrical brake included on the ARCS to stop the wind turbine in moderate to light wind conditions for maintenance. The brake works by shorting all three phases of the turbine to cause electrical resistance effectively stopping the wind turbine.

4.1.8 Control Algorithm

The ARCS integrates both wind (1.5kW) and solar (1kW) together using the LDC and intelligence from the data acquisition system and a relay. It does not divert all power to the dump load, but varies the power to the dump load depending on the state of the battery and power from the input sources to charge the battery using the PWM scheme. The renewable power is used on a priority base where power from the wind turbine is used first. This is because a wind turbine has to be under load at all times or it will over speed and spin out of control, damaging itself. The second resource to be used is solar because a solar array can be turned off like a switch without any repercussions where there are no moving parts. Due to this reasoning, the solar is used if the extra power is required. If the batteries are fully charged and the wind turbine is dumping its power, the solar panels don't need to be engaged. If the solar is not connected and there is no wind or the battery voltage is less than 92% then the solar is connected. If the solar is not connected and the batteries are greater than 92% or wind power available, the solar is not needed because the wind power is active and there is a possibility that the battery could become overcharged where the dump load is unable to handle that amount of power from both the wind and solar when the battery is almost full. If the solar is connected it has to be sure that the battery is not charged more than 95% and that the wind power is not active. This difference in voltage (92% and 95%) is so the solar is not connected and disconnected repeatedly due to the voltage dropping when the solar is disconnected and the voltage increasing when the solar is reconnected. This keeps the system from going unstable switching off and on repeatedly. If the wind turbine is active, it can produce up to 1000 watts of power quickly, and if the batteries are almost fully charged the solar cannot be active due to the dump load regulator and resistive dump load not being able to handle that amount of power. Figure 35 shows the flow of the solar algorithm and how it interacts with the wind.

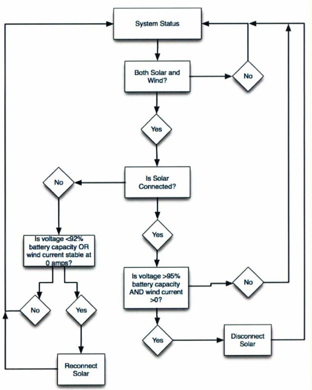

Figure 35: Solar Control Flow Chart

4.1.9 Software (flow charts, initialization, safety features etc.)

There are two parts to the software. The firmware, and the Graphical User Interface (GUI). The software was not a part of this research. The research concentrated on the hardware design and implementation. The software was a necessity in order for the ARCS to work. Philip Crowley of WES Power Technology Inc. did most of the programming for both the firmware and GUI.

4.1.9.1 Firmware

The firmware is the software that is programmed on the hardware. This allows the microcontroller to interpret the data from the data acquisition system and send the data to the memory, LCD screen, and to the computer. The language used to program the hardware is a C programming language. Figure 36 shows a flow chart of how the menus structure is organised, and figure 37 shows a screen shot of the LCD display.

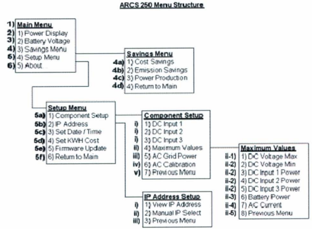

Figure 36: Firmware Menu

Figure 37: LCD Screen

4.1.9.2 Graphical User Interface (GUI)

The GUI was used to display the information from the ARCS on a PC for easy data collection and viewing. Figure 38 shows the main overview screen of the systems and provides power information for all components hooked into the ARCS.

Figure 38: Main Screen

Further detail is available for each component as shown in figure 39.

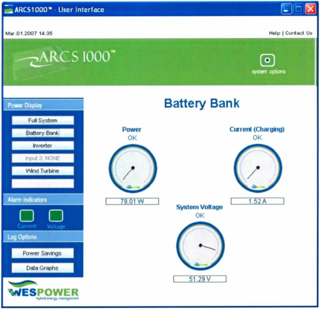

Figure 39: Detail Screen

The Alarm indicators underneath the input names are to show if one of the maximum voltage or power levels has been surpassed. The "Over Voltage Indicator" blinks if the system voltage goes above the entered maximum value on the ARCS. The "Over Current Indicator" reacts similarly if the power input or output from any of the above inputs exceeds the maximum value entered for each on the ARCS.

The “Power Savings” and “Data Graphs” buttons are used to show a graphical or textual view of the logged data. The Emission Savings screen is shown in figure 40, and shows graphs of the emission savings from any renewable source connected to the ARCS. The savings types can be selected, as well as data individual to each renewable source or all together. Data can be viewed cumulatively over different time intervals or through distributed totals over the same intervals. The emission savings is based on the North American Model of generated power, and how much electricity is used from renewable instead of from the grid.

Figure 40: Emissions Savings

History graphs of the voltage, current and power levels over different time intervals, as well as a text view of each statistic over the life of the system is shown in figure 41.

Figure 41: Power Graph

Chapter 5

5.0 Performance and Results

5.1 Performance Analysis

This section presents the results of operation of the ARCS as well as data collected from the test system, and the Davis Vantage Pro Weather Station. The system performance is shown through testing and data collection from the ARCS.

5.1.1 Data for December 2006

The data collected is for the period between Dec 19, 2006 and Dec 31, 2006. Data was not available for the entire month due to development of the software for data logging and download that was completed for use on Dec 19. This data timeframe is adequate to show the performance of the ARCS, as its performance remains similar during any other dataset throughout the year.

This data was collected from the ARCS data logging capabilities, collecting current data from its current sensors and voltage from its voltage sensors, keeping the information in the memory. This was later downloaded using the software in half hour intervals. Many more data points could also be obtained from the ARCS by leaving it connected to the software on the computer. The computer GUI allows data capture over one minute interval. Wind speed data was also collected from the Davis weather station in one minute intervals. The data was analysed from the weather station by averaging the wind speed over half hour intervals to match the data from the ARCS to obtain a power curve and performance data.

5.1.1.1 Wind Speed for December 2006

The wind speed was obtained from the Davis Vantage Pro Weather Station installed near the Southwest Wind Turbine on a tower. The speed was measured in km/h and logged every minute.

Sources of Error:

The wind speed data may contain a variance due to the location of the anemometer. The position of the anemometer is approximately 6 feet from the top of the building (National Research Council – Institute of Ocean Technology, St. John's, NL) on the west edge. When there is a wind from the direction West, North, or South there is turbulence caused by the wind hitting the side of the building causing the speed of the wind to slow down and hence resulting in a slightly lower reading. When the wind is from the East, there are no obstructions, and the wind flow was steadier. Icing and resistance due to heavy snow may also affect the reading of the wind speed. These concerns are minimized because the wind turbine also feels the same effects as the wind cups from the anemometer.

Figure 42 and 43 show the data collected from the weather station. Figure 42 shows the raw data collected from the weather station from Dec 19 – Dec 31, 2006. Figure 43 shows the average wind speed over half hour intervals for each day to make the data more manageable and easier to read.

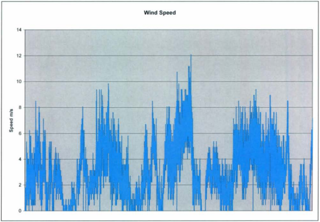

Figure 42: Wind Speed, Dec 19 – 31 in min intervals (Raw Data)

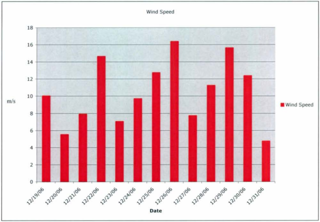

Figure 43: Wind Speed (Daily Average)

5.1.1.2 Power from Whisper 200 for December 2006

The power for the Whisper 200 was measured from the ARCS. The power is calculated from the voltage and current (Power = voltage x current). The current was measured using the Hall Effect sensors, and the voltage was measured using a voltage attenuation voltage divider circuit. The current was measured in amps, voltage in volts and power in watts.

Sources of Error:

The current data may contain a variance due to the location of the turbine. The position of the turbine is approximately 12 feet from the top of the building on the south edge. When there is a wind from the direction of South there is turbulence caused by the wind hitting the side of the building causing the speed of the turbine to slow down causing a slightly lower reading. When the wind is from the East, West, or North there are no obstructions, and the wind flow is steadier. Icing and resistance due to heavy snow may also affect the speed of the turbine. These concerns are minimized because the anemometer also feels the same effects. There is also error caused by the circuitry on the ARCS. The voltage attenuation circuit uses two 1% resistors giving a $\pm$ 1.42% error ($\sqrt{[(1)^2 + (1)^2]}$), and the Hall Effect sensors has a max error of $\pm$ 9%. Therefore the power has a total error of $\pm$ 9.11 % ($\sqrt{[(1.42)^2 + (9)^2]}$). This error is minimized by calibration of the Hall Effect sensors, voltage circuit, and power software algorithms for the output.

Figure 44 shows the raw data output of power from Whisper turbine using the ARCS. A moving average is also shown with a lag of 65 points due to the first point on the average being made up of the first 65 points of raw data. Figure 45 shows the compiled data from the average power for each day to make the data more manageable. The two following graphs show the power of data collected for Dec 19 – Dec 31, 2006 on the Whisper 200 (scale not visible due to number of datapoints).

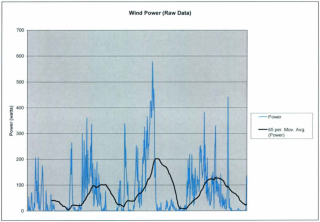

Figure 44: Wind Power, Dec 19 – 31 in min intervals (Raw Data)

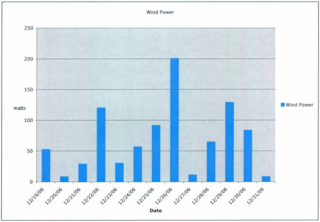

Figure 45 Wind Power Compiled Data

5.1.1.3 Wind data vs. Power Data

The following chart shows the correlation of wind speed and turbine power. It can be seen that the speed follows the same curve as the power output from the turbine as expected. This is done using the averaged data, where there is no need to show a detailed comparison of wind vs. power output, just to show a trend that the turbine was working correctly by following the same pattern as the wind speed.

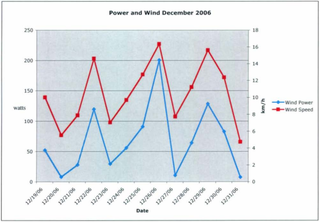

Figure 46: Wind Power and Speed

5.1.1.4 Power Curve for Whisper 200

Figure 47 shows the power curve of the Whisper 200 from data collected from the weather station and the ARCS 1000. The y-axis shows the power output and the x-axis shows the wind speed converted to m/s. This makes it easier to compare it to the factory power curve shown in figure 48. A curve fit of 4^{th} order polynomial was used to produce the most accurate curve fit of the same profile of a power curve as from the factory power curve. This curve fit in figure 47 does show the same characteristics for a power curve.

The last two data points are extracted by observation of the turbine and weather station in high winds. This manual instantaneous reading was taken to show insight at higher wind speeds. The manual method was used because in order record such a high value, the wind and power output would have to be sustained for over 30-minutes at over 1200 watts average which is close to impossible using an uncontrolled environment such as the weather.

Comparing the data from the ARCS and the factory data, it is clear that the ARCS had much better power output and performance. This was critical to making the system operate more effectively and increasing the payback of the investment. The ARCS performs as designed. With the higher output at lower wind speeds, the turbine functioned normally even though it exceeds its power rating when the wind reaches the top of the curve. The dump voltage can be adjusted to allow optimal power output from the turbine to dump sooner allowing the extra power from the low wind speeds and not from the high wind speeds.

Further analysis of the power curve showed that the start-up speeds for the Whisper 200 was approximately 1.4m/s. This is much lower than the factory start-up speed of 3.4m/s. This is achieved by the LDC starting the turbine with no load, and then slowly loads down the turbine as its speed increases. When the wind speed increases from 5 m/s to 10 m/s the output power increases from 200w to 1000w very linearly. Above 10 m/s or 1000 w the graph starts to flatten out horizontal before it falls off. This is caused by the furling action of the wind turbine spilling the wind as a means to help control the rotor speed and power output in a mechanical way. As the power increases the LDC also increases the load on the turbine in order to keep its speed under control.

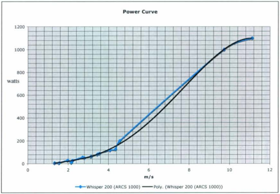

Figure 47: Power Curve

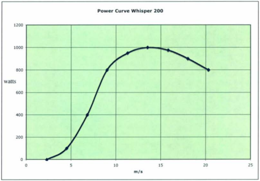

Figure 48: Factory Power Curve

5.1.2 Other Useful Data

5.1.2.1 Solar Data

The following figure shows a typical solar power profile for winter. It is shown from the graph that the most intense solar power is produced at noon, and then the power quickly drops off. This data is obtained from Hall Effect sensors on the DC solar output lines. The solar panels measured are two 110 W Evergreen solar panels over 24 hours. The power in the figure does not show the maximum power due to the season and due to cloud cover during the day, reducing down the average power recorded.

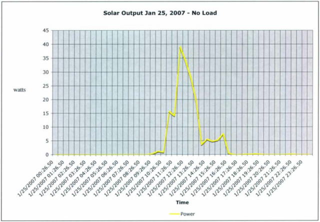

Figure 49: Daily Solar Output

5.1.2.2 Grid Load Data

Grid load data was included in this thesis to show what power consumption of a 2200 sq foot home two story home (including the basement) with electric heat on programmable thermostats, energy lighting, R50 attic insulation and R21 in all walls with energy efficient appliances. This will allow a comparison of an ARCS 1000 system power production verses power consumed in an energy efficient house.

5.1.2.2.1 Weekday Load Data

The following data was obtained using Hall Effect sensors and a data logger on a 220 VAC system with two hot feeds Line 1 (120 VAC) and Line 2 (120 VAC) of incoming power from the grid. The following graph shows the average power usage per half hour on a weekday during the winter in Newfoundland (January 18, 2007). The graph shows that power starts off high, drops off quickly as occupants go to sleep, and peaks in the morning when heat comes on and the occupants get ready for the day. During the work hours, power usage is at a minimum, and then peaks to its highest in the evening when the occupants arrive home from work. This is the typical load pattern for an energy efficient home.

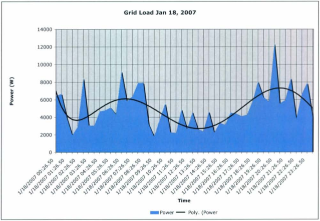

Figure 50: Actual Load Data (Weekday)

5.1.2.2.2 Weekend Load Data

Figure 51 shows the average power usage per half hour on a weekend during the winter in Newfoundland (January 21, 2007). The graph shows that power ramps up in the morning, and then drops off slightly as the occupants go about their day, than power increases in the evening. During the day light hours, power usage is higher than the weekday, but is reduced due to daylight and less demand for heating, then peaks to its highest in the evening. This pattern is similar to a weekday profile but during the daytime hours the power does not drop off considerably. This is the typical load pattern for an energy efficient home on the weekend.

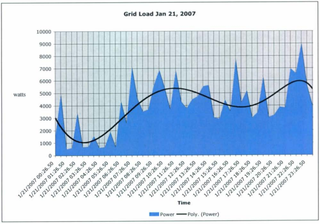

Figure 51: Actual Load Data (Weekend)

5.1.3 Data from the ARCS 1000 Software and Analysis

Data from the ARCS 1000 was collected internally in memory from all sensors. The ARCS will then compile and calculate various types of useful data such as power calculations, greenhouse gas emission savings, cost savings, etc. It can then produce graphs of the history of the system performance over time. These graphs, depending on the time range, have a very wide average. For example a daily graph will show only every half hour point; a weekly graph will show the average for each day. This was implemented this way due to limited storage memory on the ARCS 1000 to allow a total of a year's history to be saved without a download to a computer. All graphs are shown on the Graphical User Interface on the PC. If the data is regularly synchronized with the ARCS Software on a PC with the ARCS unit, data storage can be almost unlimited.

5.1.3.1 Battery Voltage

The battery voltage for the system is a nominal 48 VDC. At full charge the voltage will be approximately 58 VDC. We can see from the graph that the voltage remains constant for the week. This indicates that there was very little load on the system, and the wind turbine was able to maintain the load. There is one time that indicates a zero voltage; this was due to the system being disconnected briefly. All data is taken over an average of 5 minutes. The reason the graph is course in nature is due to the limited memory storage available on the ARCS. The data is stored in memory at intervals of 5 minute averages, and then it is downloaded to the software to display the information graphically. It takes the reading every second and calculates a 5 minute average to store in memory.

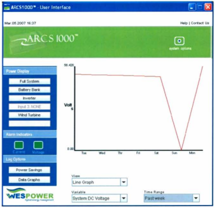

Figure 52: Battery Voltage

5.1.3.2 Battery Current and Power

The battery current for the week (Feb 26 – Mar 5) is shown below. It shows that the current draw was very small, indicating that the battery is fully charged. The corresponding power graph follows the same pattern as the current graph because it is a calculated value of current times voltage (P = V x I). This information is useful in showing the load on the battery, and determining that the battery capacity is correct. If the current draw is too heavy, the battery life will be reduced and the battery may be damaged. Typically it should not exceed 50% of the rated amp/hour of the battery (Carl Reuter, 2000).

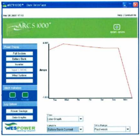

Figure 53: Battery Current (Week)

Figure 54: Battery Power (Week)

5.1.3.3 Inverter Current and Power

The following figures show the load demand on the system for the week of Feb 26 – Mar 5. It shows that early in the week there was a small load on the system and then there was another small load on Monday. This was an 18" fan with three speeds that is plugged into the system. It can be seen from the above graphs that the current drops slightly, where the current is directed toward the load, but the battery does not change direction, i.e. discharge. This means the turbine was capable of providing most of the load. This graph also determines if the inverter is sized correctly for the load. If the load is reaching the maximum power rating of the inverter often, a larger inverter maybe required. This is useful in maximizing your systems performance.

Figure 55: Inverter Power

Figure 56: Inverter Current

5.1.3.4 Wind Current and Power

Figure 57 shows the current and power output for the week (Feb 26 – Mar 5). It can be seen that the average power is very low over each day. These days had very little wind and only show an output of 5 – 6 watts out of a possible 1000 – 1200 watts. All power, even a small amount is useful to help keep the batteries toped up, but if the average power over an extended period of time is evident (several months), a renewable system will not produce useful power. This indicated that the average wind speed is less than 2 m/s for this week from the power curve of the turbine.

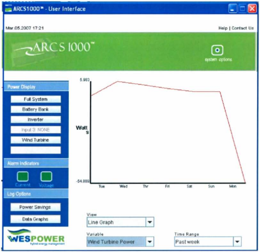

Figure 57: Wind Power (Week)

5.1.3.5 System Data and Performance

Figure 58 shows how the wind power affects the system and how the ARCS provides control to the system. The figures below show wind power from the turbine, and battery power. It is shown that on Feb 19, a total average power was 589 watts from the wind turbine and that the battery took 334 watts during charging. The remaining 255 watts was dumped by the LDC circuit due to the battery being almost fully charged using the charging circuit. This limited the current going to the battery to prevent it from becoming overcharged by pulsing the dump load at around 43% duty cycle. These graphs show how the performance of a renewable energy system can be tracked and a check that all systems are working correctly.

It can be seen from figure 58 and 59 that the ARCS is controlling the turbine and regulating the battery. When a gust of wind from the wind turbine is produced, excess energy can be produced very quickly and has to be dumped to a resistive load in an effective manner to prevent overcharging of the batteries and speed regulation of the wind turbine. Without a dump load the battery would indicate all the power going to the battery, causing the battery to overcharge possibly causing damage to the system.

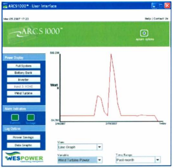

Figure 58: Wind Power (Month)

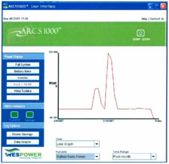

Figure 59: Battery Power (Month)

5.1.3.6 Energy Production, Savings and Greenhouse Gas Emission Savings

A key factor for a renewable energy system is to show energy production, cost savings and greenhouse gas (GHG) emission savings. Figure 60 shows the power produced from the wind turbine in watt – hours for every hour. This is calculated by taking the average power generated divided by the number of hours operation. This will show the amount of power produced from the wind turbine and how much it contributes to the overall system. This can be compared against the energy meter on a home to see the reduction in energy usage. The second graph shows the cost savings in dollars and is calculated from the local rate from the utility entered into the ARCS. This is the cents per kilowatt-hour multiplied by the power produced that is consumed. This is the amount of power that is not provided by the grid but by the renewable system if grid connected. The final graph shows an estimate of savings of greenhouse gas emissions (carbon dioxide, sulphur dioxide, nitrous oxide) by not using power from the grid, but from renewable sources. These values are based on power from the grid that is not used, thus saving fossil fuel from the generation stations. The calculation is based on the North American grid and the percentage of power that is generated from fossil fuel. This is always an estimate due to the unknown status of the fossil stations producing power; all are not operating all the time. Power utilities tend to uses other methods of generation first such as Nuclear or Hydro before using power from fossil stations to save on fuel and to help the environment (Sustainable Development – OPG, 2006)

Figure 60: Power Produced (24 hours)

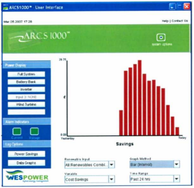

Figure 61: Cost Savings (24 hours)

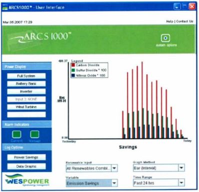

Figure 62: GHG Savings (24 hrs)

Chapter 6

6.0 Conclusions and Recommendations

This chapter first presents some conclusions based on the results of the data from Chapter 5 and the design intentions of the ARCS from Chapter 4. A comparison of other controllers is also included in the chapter to show how the ARCS compare to other controllers. This chapter provides recommendations for further research, and what wasn't achieved from the testing of the ARCS.

6.1 Summary and Conclusions

The data obtained from the ARCS shows that a hybrid system with wind and solar power makes management of a hybrid system easier and more manageable. This is made possible by the architecture of the ARCS by easily allowing both wind turbine and solar panels to connect to the one controller with all the necessary control, safety breakers, power management software, and integration. The data shows that the ARCS 1000 can improve the power curve of a wind turbine and effectively charge deep cycle lead acid batteries. With the onboard TCP/IP port, data can be logged and a history of system performance obtained. This shows if the system is adequate for the load and if the system is working correctly. The power management software also protects against premature failure, and warns if there is a system error.

The ARCS has been developed to provide a solution capable of managing existing conventional and hybrid renewable energy sources and power storage systems, into a seamless functional intelligent system (see Figure 63). This thesis focused on providing a solution to manage wind and solar power sources to the entry level and fast-growing home residential/cottage user.

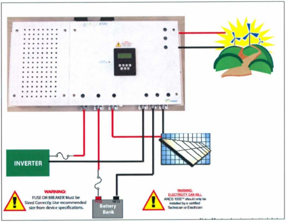

Figure 63: ARCS

The ARCS has been developed as a power management system for cottages, boats, or as a power supplement for homes. This involves small renewable energy sources as a main or supplemental power source that is not connected to the grid. The solution provides active monitoring of the power sources in the system, and controls their use in an efficient manner, allowing the user an easy way to control and keep track of their power consumption and availability. The technology developed in this thesis provides a practical and convenient solution towards the existing problem of integrating larger renewable energy sources together with other power sources.

Figure 64 illustrates the system architecture and the relationship between the ARCS and renewable power sources, storage batteries, existing advanced power electronics (inverter), and the load. ARCS can work with various configurations of systems, such as systems with or without grid-tie or battery banks, solar, wind, etc.

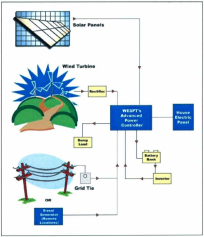

Figure 64: A.R.C.S. Architecture

This thesis describes the research of an innovative controller for small sized renewable energy systems (2.5 kilowatts or less) to allow for power systems in homes/cottages to become more reliable and easier to operate. The system is fully automated, and allows interaction with the energy system. The final result can handle up to 2.5 kilowatts of power with complete display of system status, information and history which can be accessed remotely through a communication network.

This thesis has covered the hardware design of the hybrid controller for 1.5kW of wind and 1kW of solar, optimal lead acid battery charging and optimal power usage from the wind turbine.

The results showed that the power output from the wind turbine matches or exceeds the design power curve for the tested turbine as shown from the peak power output, and the power at lower wind speeds (Figure 47 and Figure 48). The results also show effective wind turbine control and battery charging (Figures 58 and 59). The combination of solar power added complexity, but allowed for additional power combinations to make use of solar energy as a viable power source. Hybrid systems (wind and solar) increase reliability and power production versus stand alone solar or wind systems. Reliability is increased due to the reduction of multiple controllers to one controller and multiple sources of energy. Traditionally hybrid systems need a wind controller, a solar controller, and a battery charger. Combining multiple single purpose controllers to work together is very challenging and often does not work correctly together, as the following quote states. "Hybrid systems have a 65% or more failure rate, with failures due to components failing, poor maintenance, and inadequate support by system suppliers after installation." (Nelson, 2002). The ARCS Controller removes many of these technical barriers through a significant increase in intelligence ability and a reduction in component requirements. Through the ARCS solution, only one controller is needed. The ARCS Controller has wide functionality, intelligent control, variability, and scalability necessary to manage several components (necessary in most systems) and provides many integration features which increases the reliability and support through combined control to allow a more easy to manage system.

6.2 Feature Comparison

The following table below shows a comparison of the ARCS controller with other controllers of similar class.

Table 10: Controller Comparison

Products >>>	**Lakota Commander**	**Southwest Power EZ-Wire 120/1600**	***ARCS 1000***	**Southwest Power EZ-Wire 200 ***
v Options v				
Wind Turbine (Designed for)	Lakota	Whisper 100/200	Any (up to 1.5kW)	Whisper 500
Wind Turbine Capacity	900W (1.3W Peak)	1kW (1.2kW Peak)	1.5kW Peak	2.4kW (3.2kW Peak)
Load Resistor Capacity	2kW	1.6kW	1.8kW	Not Included
Solar Power Capacity	0	400W (not recommended or designed for)	1.5kW Peak	1kW Peak
Inverter Connection	No	No	Yes	No
Total Power Rating	2kW	1.6kW	3kW	4.2kW Peak
12V / 24V / 48V Options	Yes / Yes / Yes	Yes / Yes / Yes	No / Yes / Yes	Yes / Yes / Yes
Battery Charging	2-Stage	2-Stage	2-Stage	2-Stage

Wind Turbine Break	Yes	No	Yes	Yes
Wind Turbine AC Rectification	Yes	Yes	Yes	Yes
Wind Turbine Diversion Switch	No	Yes	No	No
Load Resistor Fan	Yes	No	Yes	No
Display	Analog	Digital (Extra Cost)	Digital	Digital
Menu Display System	No	Yes	Yes	No
Battery Voltage Monitoring/Display	Yes	Yes (with Display)	Yes	Yes
Battery Current Monitoring/Display	Same As Wind Current	Same As Wind Current	Yes (Separate Measurement)	Yes
Inverter/Load Current Monitoring/Display	No	No	Yes	Yes
Wind Current Monitoring/Display	Yes	Yes (with Display)	Yes (Separate Measurement)	Yes
Solar Voltage Monitoring/Display	-	No	Yes	No
Solar Current Monitoring/Display	-	No (Combined with Wind, with Display)	Yes	Yes
Power Displays	No	Wind (Solar Combined if used)	All Components	No
Manual Battery Disconnect	No	No	Yes	No

Graphical User Interface (PC)	No	No	Yes	No
Automatic Inverter Disconnect	No	No	Selectable Option	No
Automatic Solar Disconnect	-	-	Yes	No
Manual Solar Disconnect	-	-	Yes	Yes (2 Breakers, 500W each)
Audible and Visual Problem Alarm	No	No	Yes	No
Data Logging	No	No	Yes	No
Cost Savings Estimation	No	No	Yes	No
Emission Savings Estimation	No	No	Yes	No
Retail Cost				
* The EZ-Wire 200 is designed for larger wind turbine output capacity than the ARCS 1000 or other controllers in this comparison, but is comparable is other aspects.				

6.3 Recommendations

Further research could be done to see how the ARCS would reduce the power consumption from the grid. Time and resources did not allow for this to occur for this research. Comparisons can then be made once enough data has been collected to see the results, reduction and effectiveness of the ARCS installed in an on-grid home.

The effect of multiple wind turbines and different size wind turbines as well as different solar cells is recommended for further research. Different turbines have different characteristics as do solar panels.

It is recommended that further work be performed in order to improve on the current design. Such things that can be considered are fuzzy logic control, improved solar and wind integration, automatic shutdown of system upon alarms. Other methods of control can also be explored to improve the response and the integration of various renewable sources.

The ARCS has gained great interest as a commercial product. There are currently several units in the field being tested by customers. A spin off product, used to monitor renewable power systems, has been very popular in the telecom, security, residential and commercial markets. To date there are approximately 60 units sold worldwide.

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