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Small-scale hybrid alternative energy maximizer for wind turbines and photovoltaic panels

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SMALL-SCALE HYBRID ALTERNATIVE ENERGY MAXIMIZER

FOR WIND TURBINES AND PHOTOVOLTAIC PANELS

by

ROSS KERLEY

A thesis submitted in partial fulfillment of the requirements
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ABSTRACT

This thesis describes the creation of a small-scale Hybrid Power System (HPS) that maximizes energy from a wind turbine and photovoltaic array. Small-scale HPS are becoming an increasingly viable energy solution as fossil fuel prices rise and more electricity is needed in remote areas. Modern HPS typically employ wind speed sensors and three power stages to extract maximum power. Modern systems also use passive rectifiers to convert AC from the wind turbine to DC that is usable by power electronics. This passive system inefficiently wastes power and introduces damaging harmonic noise to the wind turbine. The HPS described in this thesis does not require external wind speed sensors, and has independent wind and solar Maximum Power Point Tracking (MPPT). It converts AC from the wind turbine to DC with a Vienna rectifier that can be controlled to improve efficiency, allow MPPT, and allow Power Factor Correction (PFC). PFC all but eliminates the harmonic noise that can damage the wind turbine. A prototype HPS was built and evaluated that combines the two renewable sources in such a way that only two power stages are necessary, the Vienna rectifier and a step-down converter. This thesis describes the prototype and reports the results obtained.

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1   INTRODUCTION

Affordable wind and solar Hybrid Power Systems (HPS) are addressed in this thesis. Multiple energy sources, such as photovoltaic panels, wind turbines, generators, and the power grid, can be combined to produce reliable electricity in remote areas. Additionally, through the use of renewable energy sources, humanity can lower its dependency on Earth's limited supply of fossil fuels. This thesis focuses on affordable off-grid generation from wind and solar energy.

This project was initiated as a continuation and extension of the 2009 Future Energy Challenge. That challenge involved the creation of a power electronic interface to maximize power from a 300W wind turbine to either a 12V or 24V battery [IEEE, 2008]. In addition to competing for the most power transmitted, a $20 manufacturing cost limit was imposed. The converter that won that competition is studied and redesigned as a solar and wind hybrid converter through the course of this thesis. This additional functionality would normally come at a high price, but because of the particular topology that won the 2009 FEC, minimal hardware modifications need to be made. However, new control algorithms need to be created in order to maximize the power from two renewable energy sources using one power converter.

This device, with its novel control algorithms, could be implemented to supply reliable power in areas too remote to economically connect to an existing power grid. Systems like this one are already in use on weather research buoys around North America. Wind energy complements solar power to create a more stable power supply for the National Oceanic and Atmospheric Administration's automated buoy network [Lessing, 2003]. In addition to domestic use, HPS

could be utilized abroad in developing regions to provide electricity and improve the standard of living.

1.1   Wind Energy

Humans have been harnessing wind energy for millennia. Historians suggest that windmills were used as early as 3000 years ago, but the first concrete evidence is from the Middle East in 640 AD. Windmill use spread across the world to drive machines and pump water. However, the spread of electricity supplanted windmills in many areas of the world in the early 19th century. Ironically, wind power has returned to support our growing need for electricity. The revival began at the turn of the 20th century with the Danish scientist and inventor, Poul La Cour. His early wind energy systems even had energy storage by electrolyzing water and storing hydrogen for later use. About 120 wind generator systems were in place by 1918. These early systems supplied direct current, and were installed primarily to islands or civilized areas too small or remote to afford a connection to the electric grid [Lubosny, 2003].

The process of converting wind energy into electricity involves many components. The most obvious components are the blades and hub. In a horizontal axis turbine they operate like the propeller of an airplane or helicopter, but in reverse. Vertical axis turbines are employed less commercially, because of their inefficient use of land. However, they do not require high wind velocities to begin producing power, so are more often used in residential areas and at low altitudes. The hub of either turbine orientation can be attached to a shaft on a gearbox, or directly to a generator. The gearbox is used to adapt input torque and angular velocity to

magnitudes more appropriate for the generator. The generator in a wind turbine is the component that converts rotational kinetic energy into electricity. The produced electricity can be DC, single-phase AC, or three-phase AC. Each of these has a specific application, and imposes different difficulties depending on the application. AC generators output sine-wave voltage and current on one or more wires. The frequency of this output varies with the angular rotation speed of the generator. The amplitude of these waves varies with the rotation speed and output loading.

One of the most difficult aspects of using wind turbines as a source of electricity is interfacing that power with the power grid, or with appliances that were designed to use the power grid. Throughout history this has been accomplished in two ways. First, the frequency of output power was adjusted by mechanical means. The internal generator was made to spin at one constant speed either by changing a gear ratio or by changing the pitch of the blades. In more modern systems, power electronic circuits are used to convert the amplitude and frequency of the generated power. Use of power electronics reduces the electrical efficiency by generating heat in the electrical components, but it can offer a considerable level of control over the mechanical system. This control allows more energy to be extracted at low speeds, reduced wear on the drive train, controlled shut-down of the turbine, and turbine speed control to maximize power from the wind into the mechanical system. [Dang, 2009]

Using electricity from a generator to charge a battery or battery bank can involve some difficulty. The least complicated solution is to employ a DC generator sending all power straight to the battery. This design does not allow the turbine to change speed, so it will not be able to find the

optimal rotor speed in changing wind conditions. Additionally, the battery could become overcharged and permanently damaged. Moreover, DC generators are much less mechanically efficient or reliable than an AC generator. When a single-phase or three-phase AC generator is rectified by using two or six diodes, respectively, the resulting system would be more efficient than a DC generator, but still have the same speed and overcharging limitations.

1.2   Early Maximum Power Point Tracking

Maximum Power Point Tracking (MPPT) methods have been in use for decades trying to extract the most energy possible from renewable resources. These methods can be applied to wind turbines, photovoltaic arrays, hydroelectric generators and more. In the case of a wind or water turbine, the MPPT controller continually seeks out the turbine velocity that will produce maximum power. Methods of finding the Maximum Power Point differ in convergence speed, implementation complexity, the use of analog or digital controls and the requirement of environmental sensors.

The first methods to track the maximum power point of a solar array would reconfigure the solar array depending on the available voltage and load voltage. This costly method involved complicated wiring and many relays or transistors. The earliest wind turbine MPPT controllers employed anemometers, wind speed sensors, to inform them of the wind speed. They would use this data to check a table of optimal speed or voltage values. Using the referenced data, the controller would change blade pitch or gear ratio on the turbine. Power electronic circuits came into commercial use in the 1980s and were employed in renewable energy research to optimize

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the voltage and current in order to extract maximum power. Power electronic algorithms can be applied to either wind turbines or solar panels with minimal software changes.

Many of the photovoltaic MPPT algorithms require the measurement of voltage, current or both from the panel. Each measured parameter requires additional hardware and increases the total installation cost. Additional cost factors include the use of digital circuitry and software or analog circuitry. Two common and widely used algorithms are called Hill-Climbing and Perturb and Observe. They are both straight forward methods that measure the instantaneous power, compare it to the power from the previous iteration, and then change the input voltage accordingly. They have rather slow convergence speed, but are versatile and easy to implement. These two methods are used in many modern commercial products. However, with the growth of embedded processors, MPPT methods have been able to become much more computationally complex. Authors have even applied fuzzy logic and neural networks to predict the maximum power point and converge quickly. [Esram and Chapman, 2007]

1.3   Small-Scale Wind Turbine Systems

Small-scale wind turbines can be classified by having a maximum power less than 3kW. Turbines of this size are applicable to residential use, or remote outposts. The MPPT methods for small systems may vary from large turbines because of their possibly poor or nonexistent maintenance and longer pay-out time. For example, air speed and density sensors are typically avoided in small systems, because it will take many years to recoup the additional installation

cost. Though they will typically improve the efficiency and convergence speed, the fixed sensor cost and extra bulk these sensors to be avoided whenever possible.

Algorithms employed in small commercially available power converters must not be turbine dependent. They must be versatile enough to adapt to different wind and wind turbine characteristics. Datta and Ranganathan [2003] have devised a versatile method for controlling a directly grid-tied generator. The algorithm has a fast convergence speed to adjust to changing wind. Their testing was performed on a 3kW wind turbine, with a DC motor simulating the wind. Their control method worked for the bench test without the use of air density, air speed, or any specific turbine characteristics, so it could easily be applied to commercially available products.

1.4   Photovoltaic Systems

Small photovoltaic systems can be designed for portable use, on a fixed structure, or permanently mounted to a vehicle. No matter the installation, it is desired to get the maximum amount of power from the panel with minimal cost. Just like wind turbine power systems, photovoltaic systems employ different MPPT methods depending on the situation. One particular system, by Ahmed and Miyatake [2006], employs an unloaded reference photovoltaic cell from which the MPPT controller calculates the optimum power levels. This additional cell allows a precise maximum power point to be found that is not subject to electrical noise. However, the extra cell can be costly and requires a larger surface area. As a result, this MPPT

method should be reserved for fixed installations where 10 or more individual panels are used to collect energy. [Ahmed and Miyatake, 2006]

When photovoltaic panels or any intermittent energy source are installed, special consideration must be given to their power output in relation to the required load. Often they are installed to augment the power grid, or they themselves are augmented by backup batteries or generator. For example, to supply a 550-800kW load in Lebanon, 800kW of solar panels are installed and a 400kW generator. This solution allows the maximum power to be drawn solely from solar panels during the day, and the load is typically satisfied at night by the generator. [Chedid and Rahman, 1997]

Another installation relies on photovoltaic panels, a rechargeable battery, and a non-rechargeable backup battery. This system is used on NOAA weather buoys that are placed around North America. During the day, the solar panel powers the equipment and charges the main battery. On cloudy days and at night, the main battery powers the system. However, above 50 degrees North Latitude the installations require a backup battery to provide power during long periods of darkness, such as through winter storms. Ironically, it is the weather information during those storms that the NOAA finds most interesting. As a result, research has been conducted to improve the efficiency and find alternate power sources for these buoys. [Lessing, 2003]

1.5   Hybrid Power System Basics

A Hybrid Power System (HPS) is any system that draws from multiple energy sources to power a load. They vary in size from less than a kilowatt to tens of megawatts. Often, these systems are employed to increase the reliability of renewable resources, such as wind, water or solar power. Combining multiple renewable resources increases the reliability, as does incorporating fossil fuel generators, battery banks or a connection to a power grid. Significant amounts of research have been conducted to find the most cost effective and environmentally friendly energy sources. Typically, HPS must be specifically designed for a region. Every place on Earth has different solar radiation, wind profile, water flow, and fuel prices. Luckily, HPS research has included the methodology of system sizing and selection.

One algorithm in particular, developed by Gupta, Kumar and Agnihotri [2007], calculates grid-tied or standalone systems including wind turbine, solar panels, generator, batteries, grid-tie inverter, power conditioning and dump load. The dump load is used to burn up energy if the renewable sources exceed the required load. Input parameters for this algorithm include average wind speed, solar radiation, a load schedule, loss-of-grid probability and cost of every component. This research required modeling of the various components in MATLAB. The system is simulated and components selected to produce reliable and inexpensive power.

A more comprehensive but less refined algorithm was developed by Gupta, A., Saini, and Sharma [2008]. This algorithm also takes into account renewable biomass such as wood, dung or agricultural waste. Biomass is the most common source of energy used for heating, lighting

and cooking in rural developing nations. The equations implemented in this algorithm are far more focused on cost of the energy and not at all on environmental impact or reliability. As with any algorithm, extensive data collection would be required to predict the energy usage of people that have never had electricity before. Energy supply analysis is much less demanding for this algorithm.

1.6   Applications of Hybrid Power System

HPS are often suggested for use when a region or community is too remote for connection to a utility grid. Additionally, HPS can be applied to stabilize the grid and improve the power capacity in rapidly developing areas. Each of these areas poses a unique environment for HPS and has unique energy supply and needs. These applications and areas include: weather buoys, rural Bangladesh, urban Portugal, and hamlets of India. These areas are only a small variety of the regions that have promoted the installation of HPS.

1.6.1   Case Study: NOAA Weather Buoy

The aforementioned NOAA weather buoy research paper [Lessing, 2003] discussed the addition of wind turbines to a previously only photovoltaic system. The original system charges a battery during the day, and discharges at night. Additionally, the battery discharges on cloudy days. This introduces an extra difficulty when the systems are installed at high latitudes. Winter in Alaska has short days, many of which are clouded by snowstorms. If a purely solar system was installed here, the panel and battery bank would have to be large in order to charge up during a short day and then have enough stored energy to last for several days. Above the Arctic Circle,

where there can be days or weeks of no sun, this kind of system would be prohibitively expensive, especially because the performance of batteries is reduced in cold temperatures.

The hybrid system installed on the experimental weather buoy involved two wind turbines, and the typical photovoltaic and battery setup. Each of the three renewable sources had its own charge controller to charge the on-board lead acid battery. Running all three chargers in parallel could have easily over-charged and permanently damaged the battery, except that a dummy load was installed to engage when the battery is charged. The two different turbines were installed to test the effectiveness of each at that particular location. It was a good thing that they installed two turbines because two weeks into a two month test, high winds damaged one turbine and it was not noticed until the data collection was over. [Lessing, 2003]

Strangely, the extra datalogger installed on the buoy to monitor the HPS failed. All current and voltage data was found to be corrupt after the test. Luckily, the author was able to extrapolate enough information from the regular NOAA weather data transmissions to draw a conclusion. Using solar charging current, battery voltage, and average wind speed, results were drawn about the feasibility of using a solar-wind HPS in this situation. The author was able to confidently write that wind power alone sustained the buoy for several days during a particularly violent and cloudy storm. It was during this storm that one of the turbines sustained critical damage. In conclusion, this system was improved in electrical reliability by the addition of wind power. [Lessing, 2003]

1.6.2   Case Study: Bangladesh

Remote settlements in developing countries do not typically reap the benefits of access to electricity 24/7. Humanitarian groups and the governments push for electrification of their interior, often through the use of renewable resources such as water flow, wind, and solar radiation. HPS can be installed in these areas grid-tied to improve the power grid, or off-grid to provide an isolated electric network. Ambia et al's [2010] paper on HPS in rural Bangladesh describes the design of a possible HPS and the motivation to install them in rural Bangladesh.

This paper discusses the basic power equations behind photovoltaic panels and wind turbines. In addition to these basic equations and theory behind the two energy sources, they assess the average solar radiation and wind speeds for the different regions of Bangladesh. For example, the wind speed is generally higher in the eastern half of the country and near the coast. As discussed earlier in [Gupta, A. et al, 2008], assessing the available resources is a vital step in designing a HPS. [Ambia et al, 2010]

Finally, this publication proposes an off-grid and an on-grid hybrid system. These two system topologies are primarily identical, however the on-grid system is significantly more complicated. The two systems both charge a battery bank from a wind generator and solar panels. The energy stored in the battery bank is transmitted to DC Loads, and to a DC/AC Inverter. The inverter creates AC, like the power grid, from DC power, like a battery. The off-grid system uses that power directly to power electric appliances. However, the on-grid system transmits the newly

inverted AC power to a load controller that selects whether to power appliances from the grid or from alternative energy. [Ambia et al, 2010]

1.6.3   Case Study: Portugal

The motivation for this HPS installation is to reduce the dependency on fossil fuels and other non-renewable energy sources. It has been installed in Beaufort, Portugal and all specifics have been released in this paper. Similar to [Ambia et al, 2010], this Portuguese paper [Fontes et al, 2008] has designed both an off-grid HPS and an on-grid HPS. The two systems differ in method of energy storage and treatment of the AC load. These differences are derived from the system motivation. Whereas Ambia et al were driven to create an efficient and reliable system that could help to support the grid, Fontes et al wanted to reduce a fossil fuel dependency without emphasizing increased reliability.

The off-grid or isolated HPS is identical to Ambia et al's. The solar panels and wind generator are fed through a load controller to charge batteries. Battery power then goes to DC loads and to run the DC/AC inverter that supplies AC loads. To contrast, the on-grid system does not have backup batteries. Without the batteries, solar and wind electricity passes through a load controller and directly to a grid-tie inverter. [Fontes et al, 2008]

That research paper concluded that HPS are most applicable to reduce a dependency on foreign oil. Portugal was a good example for this because it has no significant natural reserves of fossil fuels. Additional significant advantages to omitting batteries include the total cost of ownership and regular maintenance. Batteries degrade when used and require regular maintenance on their

acid levels. Because of these reasons, urban or suburban Portugal and other cities are excellent

sites for grid-tied HPS. [Fontes et al, 2008]

1.7   Thesis Overview

Renewable resources were introduced in this hybrid power system (HPS) introduction. Wind

turbine history, maximum power point tracking, small-scale wind turbines, photovoltaic systems,

hybrid power system basics, and applications of hybrid power systems were described. Each of

these topics is a component of the modern HPS discussion.

The following chapter of this thesis provides examples of the cutting edge in HPS. These

systems represent the most advanced maximum power point tracking (MPPT) algorithms and

most modern power electronic topologies. The specific problem addressed in this thesis will be

definedin Chapter 3. The following two chapters describe the approach taken to solve the

problem, and the prototype process. Testing and evaluation of the prototype HPS is described in

detail in Chapter 6. Finally, Chapter 7 presents conclusions and future research.

2   MODERN HYBRID POWER SYSTEMS

This chapter discusses the state of the art in hybrid and renewable power systems. The systems described have specific power electronic topologies, defined system architecture and control algorithms that allow them to efficiently collect energy from renewable sources and supply different electrical loads.   These modern HPS all use power electronics to interface the generated electrical energy with the grid, batteries, or any other electrical load. First in this chapter, we will discuss the hardware of different state of the art HPS. These different system architectures and converter topologies allow power to be converted and controlled. Then, state of the art HPS control systems and algorithms will be discussed.

2.1   Hybrid Power System Architecture and Topology

The architectures and topologies here have many strengths and weaknesses. The most substantial weaknesses are in system cost and overall efficiency. The efficiency differences come from the number of power electronic converter stages, and the topologies of these stages. System cost is usually directly related to size and capacity of the system, but the extreme voltage and current ratings required by some topologies are a large cost contributor as well.

2.1.1   1 kW Wind-Photovoltaic Hybrid System

Dali et al [2007] devised a 1kW Hybrid Power System (HPS) using a 600W turbine and 400W photovoltaic panel. These two renewable energy sources supply power to batteries and loads on

a 48V DC bus. Simulated and experimental results promote the control algorithms of this HPS, but the converter topologies and architecture are characteristic of a modern standalone HPS.

Electricity from the wind turbine is three-phase AC. Therefore, it needs to be rectified and the authors chose to use a standard 6-diode bridge. The resulting DC power is reduced to 48V by a Buck, or step-down, converter. This conversion process does not perform well at low wind speeds. The wind turbine voltage experiences fixed losses from the diode bridge, and must be significantly higher than 48V in order for the buck converter to push power into the 48V bus. Because of the diode bridge, the wind turbine will have a distorted power factor. This causes significant electrical loss in the generator itself because current and voltage are out of phase. However, this simple topology will perform well at high power levels because of the single buck stage. Additionally, only one converter needs to be manipulated to perform maximum power point tracking (MPPT).

Power from the photovoltaic panel is converted in a similar manner. This electricity is sent straight through another buck converter that reduces the voltage to interface with the 48V DC bus. This topology is simple to manipulate for MPPT, but has similar drawbacks to the wind generator, that under low sun exposure the converter will not be able to supply the bus.

The buck converter topology employed by both converters is less than optimal by itself. It is asynchronous, which has a fixed voltage loss because of a diode. However, improving that is trivial with the addition of a mosfet and driving circuit. This standard topology is used as a testbed for control algorithms, not optimizing the component-level power efficiency. The

architecture selected by Dali et al allows simple control of the power converters. However, because of the parallel structure, shown in Figure 2-1, this architecture has some components that could be shared between the two halves. Each MPPT converter has input and output capacitors, in addition to an inductor, mosfet and diode. The capacitors could be reduced or at least eliminated if these converters were cascaded. Some sophisticated architectures make use of different topologies to optimize the component usage [Hui et al, 2010]. Additionally, the buck converter topologies would benefit from simple modifications. The wind generator rectifier will need to be improved to increase its efficiency and its ability to extract power in low-wind conditions. [Dali et al, 2007]
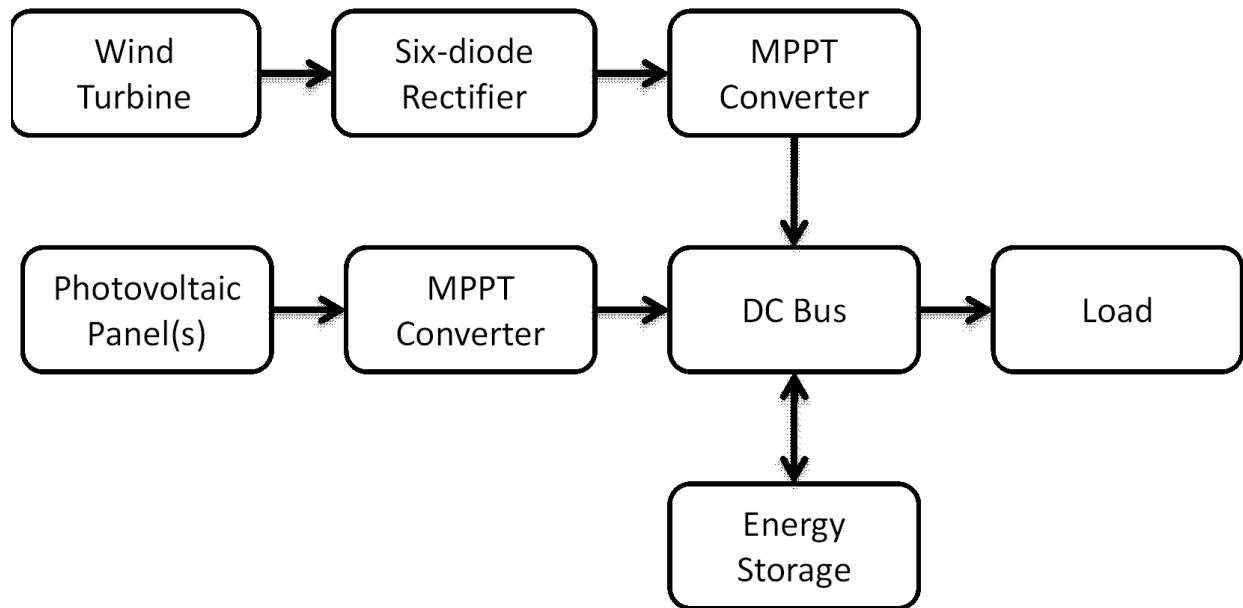

Figure 2-1: Parallel HPS architecture

2.1.2 Modern HPS Micro-grid

Hybrid Power Systems can be used to provide electricity in remote areas, such as on islands or at oases. One such island to the north of Brazil has been a testing ground for a unique HPS architecture and an isolated micro-grid. [de Souza Ribeiro et al, 2011] A micro-grid is an electrical distribution network that supplies power to a relatively small area from distributed generators and energy storage devices. Micro-grids may be standalone or grid-tied for backup. In this case, a standalone micro-grid was the only option because of the community's location on an island. The distributed generation in a micro-grid can come from many sources, including fossil fuel generators and photovoltaic panels. The optional energy storage, in the form of batteries or fuel cells, is used to buffer the micro-grid if the generating sources cannot supply enough power.

This particular micro-grid, installed on Lençóis Island in Brazil [de Souza Ribeiro et al, 2011], incorporates wind turbines, photovoltaic panels, a diesel generator, a battery bank, and inverters to power 90 households with a population of about 400. Such a modern system is intended to primarily utilize renewable sources and the battery bank, only resorting to starting the diesel generator when insufficient battery power is left. In addition to these power components of the HPS, a sophisticated monitoring subsystem logs data and makes decisions regarding the power flow depending on the current state.

This continuously running system has been effectively sized to provide redundant power to its customers. It employs both a DC bus and an AC grid that can be supplied wholly by renewable

resources or a diesel generator. The redundancies even extend to the three independent DC/AC inverters that tie the two buses together. These implementations will effectively provide electricity for decades with a low reliance on the fossil fuel generator. This architecture, and its control algorithms that will be discussed later, should be a model for both large and small scale commercial HPS. [de Souza Ribeiro et al, 2011]

2.1.3 A Cuk-SEPIC Converter for Two Power Sources

Hybrid Power Systems employing conventional parallel converter architecture, such as in [Dali et al, 2007] are simple to design, test, and control. However, by employing different topology options, the system can become more versatile and employ smaller components.

Hui, Bakhshai and Jain [2010] have proposed an alternative topology for a wind and solar HPS. This topology uses a SEPIC converter for wind MPPT and a Cuk converter for solar MPPT. This arrangement allows the two converters to share power filtering and significantly reduce high frequency harmonics applied to the turbine. These harmonics, if allowed to propagate, would increase power loss in the generator and decrease its lifespan. The SEPIC converter employed to convert energy from the wind generator is a DC to DC converter, so the three-phase AC turbine must be rectified. The authors chose a six-diode rectifier that will reduce efficiency, especially when using a low voltage generator. The interleaved Cuk and SEPIC converters employ the same number of switches as a parallel converter design [Dali et al, 2007], but reduced inductor size and number of capacitors. These topologies utilize capacitors as the primary energy storage medium, while conventional Boost and Buck converters utilize inductors.

The efficiency is comparable to Buck and Boost coverters, but Cuk and SEPIC converters offer some unique and helpful features.

One difficulty with a standard buck (step-down) topology is the inability to extract power from a low voltage input to a fixed output voltage. The inverse, a boost converter, can push power from low voltage inputs to a fixed bus. However, if the input voltage rises too high, the boost converter will not be able to push any power at all. For a HPS, the most appropriate between these is clear, because at low voltages, little power is available anyway. However, if power can be extracted from low or high voltage, there will be a more continuous supply of energy. Both the Cuk and SEPIC topologies are able to step the voltage up or down. These versatile converters still allow independent maximum power point tracking of the two renewable energy sources. One interesting characteristic of these topologies is output voltage inversion. The output power has the inverse polarity of the input power from both sources. While some power electronic applications may suffer from that characteristic, it is irrelevant to a HPS. The input power sources, photovoltaic panels and wind turbines, are by nature electrically isolated from the grid or any electrical load.

This complex and novel topology is still in the simulation stage, and the difficulties of applying it to a real-world design have not been published yet. In several years, it may prove to be a useful design when the requisite high voltage and high frequency capacitors are reduced in size and cost. Further applying this system and topology will be useful, but it requires a six-diode rectifier and offers no active power factor correction, something that further improves the efficiency of a wind generator. [Hui et al, 2010]

2.1.4   A Wind Turbine Rectifier With Power Factor Correction

When extracting power from an AC source, the current and voltage may become out of phase. This is caused by inductive or capacitive (reactive) loads that briefly store energy. A purely resistive load causes perfectly in phase current and voltage, which is the most efficient way to produce energy. Therefore the power factor of a resistor is 1.0.

$$power\ factor = \frac{average\ power}{rms\ voltage * rms\ current}$$

Any deviation from a resistive load results in a decrease in usable power for the same average current and average voltage. The loss in power results in unnecessary heating of the wind turbine and a lower maximum power point. Correcting this loss has become a great concern in the last few years, both in the conventional use of the AC grid, and when interfacing with AC wind turbines. Correction can be implemented with passive components, or actively. Adequate passive correction involves calculating an inductor or capacitor to offset the power factor distortion. Passive components are simple to implement, but have several drawbacks, including large size and limited effectiveness. The calculations required to design passive correction depend on the voltage and current of the load. However, voltage and current are highly variable from a wind turbine. As a result, active correction is the only logical option for a wind turbine. Converters with Power Factor Correction (PFC) are invariably more expensive and complex than those without, however the efficiency and increased maximum power point can outweigh the disadvantages. An analysis of the advantages and disadvantages of active PFC applied to wind turbines was performed by Gamboa in his Master's thesis. [Gamboa, 2009]

Gamboa discusses the comparison of a standard six-diode rectifier with a Vienna rectifier, or a

three-phase boost converter. A Vienna rectifier is able to independently control power draw on

the three phases and boosts the available voltage. The topology and controls for a Vienna

rectifier will be described in Chapter 4. The two rectifiers output to a DC bus, where a buck

converter steps the voltage down to charge a battery. PFC was implemented by changing the

Vienna rectifier duty cycle with the input voltage. The Vienna rectifier, in addition to allowing

PFC, boosts the input voltage to enable battery charging from a low-voltage input. This

topology could be implemented as standalone, as in Figure 2-3, because it can perform MPPT, or

simply as a replacement for the standard six-diode rectifier, as in Figure 2-4. When used as

standalone, the benefits are enhanced because of the fewer power stages and faster MPPT

control. One disadvantage to standalone operation is that the DC bus must always have a higher

voltage than the input because of the boost converters in the Vienna rectifier. This raises safety

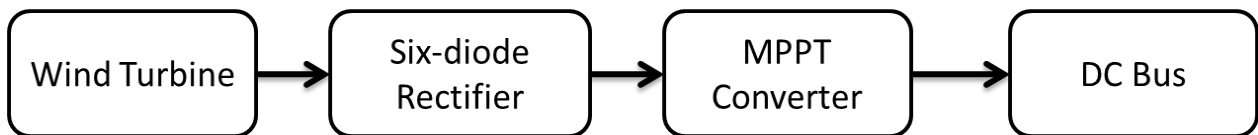requirements and may be more inefficient when charging batteries or supplying DC loads.
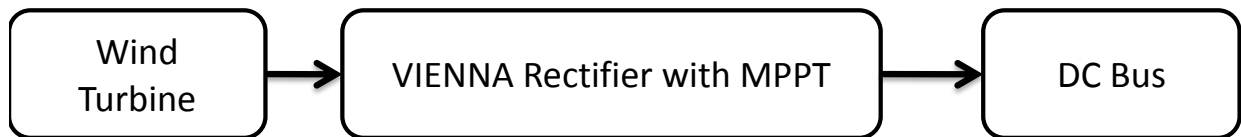

Figure 2-2: Six-Diode rectifier

Figure 2-3: Standalone Vienna rectifier

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┌──────────┐      ┌──────────┐      ┌──────────┐      ┌──────────┐
│   Wind   │      │  Vienna  │      │   MPPT   │      │          │
│  Turbine │ ───▶ │ Rectifier│ ───▶ │ Converter│ ───▶ │  DC Bus  │
└──────────┘      └──────────┘      └──────────┘      └──────────┘
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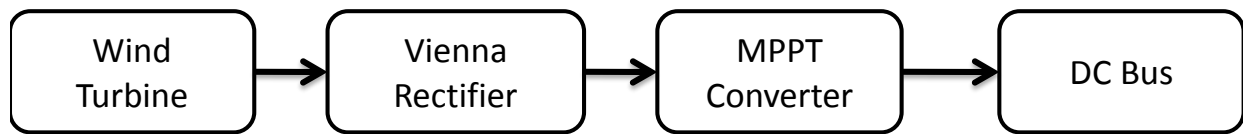
Figure 2-4: Vienna as diode replacement

Gamboa verified that the Vienna rectifier benefits outweighed the additional cost because of a

15% increase in available power from the same small wind turbine. In addition, PFC reduces

strain on the turbine, extending its usable life. Therefore, active PFC should be implemented on

future converters especially when it will replace both a diode rectifier and a discrete MPPT

converter. [Gamboa, 2009]

2.1.5 Topology Comparison

The discussed topologies and architectures each allow individual control over the energy

sources. This is essential to apply MPPT algorithms to solar and wind sources separately and

extract maximum power. However, the method of this individual control is highly variable. A

standard parallel architecture can be employed with buck or boost topologies to combine and

effectively control the inputs such as in [Dali et al, 2007]. This kind of topology, shown in

Figure 2-1: Parallel HPS architecture, employs simple topologies to control the sources and

provide energy to a load. These topologies can damage the wind turbine because of unfiltered

high frequency harmonics from the MPPT stages. Additionally, there is no allowance for Power

Factor Correction (PFC) on the wind turbine, and the discrete converters could be combined to

reduce the part count.

The damaging harmonics can be reduced without the introduction of large passive filters by employing more modern and sophisticated topologies. A Cuk-SEPIC hybrid converter is a modern alternative to conventional buck and boost topologies and offers advantages to energy harvesting applications. The damaging harmonics are reduced, and low-voltage operation is allowed, but the requisite rectifier does not allow PFC. To allow PFC, a more sophisticated rectifier must be used. There are many promising topologies for active PFC, but one proven method is a Vienna rectifier. [Gamboa, 2009] This topology can be controlled to perform both MPPT and PFC, reducing the number of converter stages and power loss. This approach may sound ideal, but because the Vienna rectifier boosts the input voltage, the DC output must have a higher voltage than the output of the wind turbine.

2.2   Hybrid Power System Controls

HPS controls are required to effectively use alternative energy. The control systems regulate voltage and current in order to maximize extracted power while protecting the electrical components in use. Each subcomponent in the HPS may need its own control algorithm that can communicate with the other subcomponents in order to work in harmony. Some control algorithms can be implemented using analog devices, such as 555 timers and operational amplifiers, but they are limited in features and are becoming more expensive. The alternative, digital control systems, has several advantages. Its small size and ease of programming has opened the door for many sophisticated control methods that push the limits of energy harvesting efficiency.

2.2.1　1 kW Wind-Photovoltaic Hybrid System

The paper by Dali et al [2007] describes the topology and control of a small wind and solar HPS. While the aforementioned parallel topology is not groundbreaking, this paper presents novel and robust energy management. The supervisor control system presented in this paper uses only voltage and current measurements to coordinate the individual converters in a safe HPS. It maximizes power to the load and battery whenever possible, but limits damaging voltage and current to the battery if necessary. The control of this system is accomplished by operating in three modes.

The system operates in the first mode when the renewable sources can be maximized. This is the case if the load is greater than the hybrid sources and the battery must be drained. This is also the case if the battery has been discharged and the renewable sources need to supply a low load, and charge the battery. Essentially, in this mode, the battery can supply or sink the difference in renewable power and load power. To stay in this mode, the measured battery voltage must be below a maximum value. If the battery voltage reaches the maximum value, the HPS controller transitions into the second mode.

The second and third modes are similar in that neither involves utilizing maximum power from the renewable resources. This is done to protect the battery and load from excessive voltage. The difference in these two modes is determined by the required load power. Mode two extracts maximum power from the photovoltaic array, but regulates the wind turbine to a lower power level. Mode three extracts minimal power from the wind turbine and less than maximum power

from the photovoltaic array. This method of reducing available power contrasts with the NOAA

weather buoy [Lessing, 2003] and the algorithm developed by Gupta et al [2007] where dump

loads are used. A dump load reduces available power by wasting it as heat. This puts the same

strain on the power electronics as running at full power, and increases heat in the system,

requiring additional cooling to prevent overheating. Changing the power level of the converters

as in [Dali et al, 2007] is much more efficient, less expensive and smaller.

2.2.2   Adaptive Control Algorithm for Wind Energy MPPT

In addition to the upper level control algorithms that guarantee harmonious interoperation of the

subcomponents, attention must be given to effective renewable energy maximization. In two

papers, Hui and Bakhshai [2008a-b] present two slightly different MPPT algorithms to be

applied to wind turbines. The first [2008a] performs a modified hill-climb algorithm while

learning a new turbine's characteristics. Once those characteristics have been acquired, the

converter can quickly adapt to a new wind speed, even if it has never experienced that wind

speed. The second [2008b] employs the same adaptive and learning algorithm, but enhances it

with two additional control loops. These novel control system components each introduce an

innovation to wind turbine MPPT.

These algorithms employ an external anemometer (wind speed sensor) to speed up the MPPT

process. A modified hill-climb algorithm finds the current maximum power point, and then

stores the instantaneous wind speed and the instantaneous rotor speed in a small table. This table

of Tip Speed Ratios, or ratio of rotor to wind speed, helps the converter find the maximum power

point when the wind changes. Hui and Bakhshai developed an algorithm that can adapt to different turbines but perform just as well as a controller preprogrammed for a specific turbine's characteristics. This algorithm has some of drawbacks that include the use of environmental sensors and not accounting for air density. Environmental sensors such as the anemometer increase the cost, size, mounting concerns, and reliability of a turbine controller. Air density accommodation is accomplished by the adaptive nature of this converter, but it has no stored data point for density. The addition of an air density sensor would allow even faster MPPT.

The two additional control loops in [2008b] do not address the large deficiencies in the adaptive hill-climbing control strategy, but they do further decrease the time necessary to perform MPPT. Hui and Bakhshai devise a Change Detection Loop (CDL) that monitors wind speed changes and determines the approximate maximum power point. The second control rule that they add in this paper is an Operation Point Adjusting Loop (OPAL). CDL references a small table of Tip Speed Ratios (TSR) and selects the closest to optimal value. Once the closest value is selected, OPAL takes over control and further refines the TSR. The refined values are stored in the table for future reference. These additional loops increase the efficiency and speed of MPPT, but the rotor and wind speed sensors are still necessary for this algorithm. [Hui and Bakhshai 2008b]

2.2.3   1-5kW Wind-Photovoltaic Hybrid System

Research has been conducted on the control systems of small standalone HPS. One such system is described in [Meiqin et al, 2008]. The two power inputs, wind and photovoltaic, are arranged in parallel as in [Dali et al, 2007], shown in Figure 2-1. The separate MPPT converters push

power to a 48V battery bank that supplies power to a DC/AC converter to create a standalone AC micro-grid. The paper by Meiqin et al [2008] describes HPS totaling 1, 3, and 5 kW. However, the control rules and algorithms remain the same. The wind turbine algorithm requires an anemometer, so is bulky and expensive. Additionally, the method of finding the maximum power point involves pre-programming the turbine specifications into the converter. However, the photovoltaic MPPT is much more versatile and sophisticated. MPPT of the photovoltaic panel is purely dependent on battery current. The solar array voltage and current are varied through a DC/DC converter to allow maximum battery current. The controller limits the current as the battery reaches fully charged. The battery is allowed to trickle charge, or charge at a low rate, even when fully charged. This prolongs the battery's usable life.

The solar algorithm presented in this paper offers an interesting control algorithm. By basing it purely off of battery current and voltage, the converter can be inexpensive, but still quite effective. Additionally, this HPS research has provided battery management algorithms to not only provide maximum power, but to prolong the life of the battery. [Meiqin et al, 2008]

2.2.4   Multi-agent HPS control

Modern HPS control system research is exploring multi-agent technology to realize complex software systems. [Jia and Chang, 2009] The agents implemented in this research are self-contained portions of software that can perform a specific task. For example, a Wind Data Collecting Agent retrieves data from environmental sensors, while a Wind Data Processing Agent converts that data to usable units and accounts for any calibration. Agents exist for all

components of the HPS control system, such as battery charging, Photovoltaic MPPT, and DC load.

This paper describes four different running modes of the HPS. They are differentiated by the renewable sources available. The standalone HPS functions in mode one if only wind energy is abundant and mode two if only solar energy is abundant. Mode three is when both renewable sources are plentiful, and mode four is when neither can support the load. In each of these modes, a battery can either charge or discharge if there is a surplus or deficit of power, respectively.

The use of agents in the manner described by Jia and Chang could reduce the responsiveness of an HPS. New data regarding load or MPPT data must be processed by five agents before changes can be applied to the power conversion process. This delay could be several times higher than the delay of an HPS control system with fewer agents, or a conventional control loop.

This method of assembling a control algorithm based on self-contained agents is convenient and structured. It improves performance and reliability of HPS control systems with good organization. However, this method may not produce the most optimized control system structure. A system created by following the multi-agent method would be stable and reliable, but not necessarily the fastest control system. Additionally, the self-contained agents may require a faster control system processor in order to achieve fast enough performance.

2.2.5   Controls Comparison

HPS control systems contain many components. The system energy path must be controlled, but the individual power electronic converters must also be controlled. Current HPS control system research has focused on reducing costly and bulky sensors, on speeding up wind MPPT, and on increasing reliability. Additionally, power factor correction in wind turbines has been the subject of recent innovation [Gamboa, 2009]. This marriage of novel topology and sophisticated control algorithms increases the efficiency and life expectancy of wind turbines.

Dali et al [2007] describes methods of individual converter control using few sensing components. This innovation allows for significantly lower initial cost of the HPS, and less maintenance. Many papers have been published about speeding up MPPT in wind converters, such as [Hui and Bakhshai, 2008a-b] and [Meiqin et al, 2008]. These papers present wind MPPT algorithms that require bulky sensors, but they use those sensors to greatly reduce the time MPPT takes to adapt to a new wind speed. However, their implementations of solar MPPT are geared to low hardware cost and small components. This direction of research also needs to be followed for wind MPPT.

System-wide controls have also progressed significantly. Algorithms are now more concerned about battery life than before. The control systems from Meiqin et al [2008] and Jia and Chang [2009] support this claim. The first describes a standalone HPS control system that creates an AC micro-grid from 1-5kW of renewable sources, and a backup battery. HPS battery banks are usually composed of lead acid batteries. This battery chemistry should not be over-discharged,

or over-charged. Doing either permanently damages the battery bank. The second describes a multi-agent control system that compartmentalizes the control algorithms to improve reliability of HPS. Programming standards, such as the multi-agent method, often prevent errors from propagating throughout the system, but they impose additional overhead that consumes memory and microprocessor cycles.

2.3   Modern Hybrid Power Systems Summary

HPS research has grown significantly in the last five years. HPS architecture has expanded to allow individual MPPT of the renewable sources, and advanced battery management. Converter topologies have advanced to allow Power Factor Correction (PFC) of AC wind turbines. This advanced technology is usually applied to grid power consumption in order to increase efficiency and reduce strain on the grid. When applied to wind turbines, it increases their efficiency and life. Additional topology advances have included implementing topologies that offer inherent advantages to HPS. A Cuk-SEPIC hybrid in [Hui et al, 2010] offers reduced wind turbine harmonics and cost compared to a traditional parallel architecture. The cost savings come from sharing components between the two interleaved converters. In addition to cost savings, size and heat dissipation can be reduced.

Control system advancements have included reducing the number of sensing components, speeding up MPPT, extending battery life and increasing reliability. Unique control algorithms have been created to reduce the number of costly current sensing components [Meiqin et al, 2008]. Significantly increasing the speed of MPPT comes at the cost of an external anemometer.

This significant addition decreases the reliability and increases repair costs, so should be avoided in future research.

Future research should focus on further reducing the cost and size of converters while maintaining speed of MPPT. Reducing the cost further also includes increasing reliability so that fewer repairs will be needed throughout the lifetime of the HPS. PFC is an essential technology for reducing cost and increasing efficiency. An increase in efficiency will allow a smaller wind turbine to provide energy. Additional experiments in interleaved converters may allow more part reductions, further lowering cost and wasted energy.

3   PROBLEMS WITH HYBRID POWER SYSTEMS

The first two chapters of this thesis introduced Hybrid Power Systems (HPS) using renewable sources while exposing the weaknesses of modern technologies. These systems are typically composed of at least three individual power converters that collect wind and solar energies from wind turbines and photovoltaic panels and combine them to provide stable power. These converters employ various methods of Maximum Power Point Tracking (MPPT) to extract the most power possible from a particular wind speed and intensity of solar radiation. Current research has focused on speeding up MPPT, increasing efficiency, lowering cost and designing stable control systems for HPS. This chapter describes some general problems with HPS, the specific problem that we address in this thesis, the hypothesis, and our contributions to the field.

3.1   General Problem

Remote communities, isolated research stations and rapidly developing nations have an increasing need for reliable and affordable energy. Often, extending an existing power grid is not cost effective, so electricity must be obtained locally. Renewable energy sources, such as moving water, solar radiation, or even geothermal activity, are freely available in our environment, even in remote areas. In many of these remote areas, wind and solar energies are complementary. During the peak-sunshine hours, wind can be stagnant. However, on cloudy days or at night, wind tends to fill the energy void. Harnessing these two energy sources can provide a much more stable supply of electricity than either could alone. HPS should be used in these situations, but the initial costs and recurring costs, such as turbine repair, can be too high

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for developing communities to afford. Therefore, HPS cost and reliability need to be improved

if they are ever going to provide plentiful and clean electricity for developing and remote

communities. Increasing efficiency is an additional way to reduce cost, because a more efficient

converter could produce more power for the same initial investment and maintenance cost.

Modern HPS have several deficiencies in hardware and software that result in these weaknesses.

Some of the hardware shortcomings include topology allowance for Power Factor Correction

(PFC), inefficient power topologies, and excessive components that could be eliminated by

changing the system architecture. These cause turbine wear, increase power loss and require

large heat sinks. They ultimately result in large and expensive HPS. Control systems are too

reliant on external wind sensors, expensive current sensors, and bulky software. These result in

unreliable, expensive, and slow converters.

3.2   Specific Problem

This thesis addresses some of those problems. Specifically, it addresses HPS cost and stability.

These two deficiencies are most easily addressed by reducing the number of parts through a

novel HPS architecture, while creating a stable control algorithm.

Modern small-scale wind turbine power converters lack controlled rectification. Controlled

rectification allows Power Factor Correction (PFC) and current shaping. These two technologies

are in widespread use for grid power, but not for small-scale wind turbines. A poor power factor

is caused by either a capacitive or inductive load, and is characterized by the current and voltage

being out of phase. A poor power factor can cause extra loss in the turbine, and prevents the

extraction of maximum power. Current shaping goes hand-in-hand with PFC. It makes the current follow a sinusoidal pattern, instead of a square-wave, which is produced by diode rectification. Square-waves have high harmonic content that causes the wind turbine to accelerate and decelerate at a high frequency. As a result, irregular forces and angular velocity cause damage to the turbine gear box and can apply excessive irregular torque to the turbine blades. Active rectification can significantly reduce that harmonic content and increases power output from the system. Additionally, inefficient HPS architectures require large volume for heatsinking and for larger power stages. They have more conversion stages than necessary to accomplish the same MPPT and voltage conversion.

Some control algorithms can also require large sensors that increase the size and cost of HPS. Many modern turbine MPPT control algorithms require a physical wind-speed sensor that should be mounted near the turbine, but far enough apart that they do not interfere with each other. External wind sensors greatly increase the initial cost of a system, repair cost, and frequency of repairs. Additionally, many control algorithms require numerous current sensors, which can be either inaccurate, or add significant cost.

3.3   Hypothesis

A series-architecture Hybrid Power System can be designed to eliminate a power stage without suffering a loss in stability, efficiency, or Maximum Power Point Tracking ability. This architecture can also reduce cost by reducing the number of current sensing circuits.

3.4 Contributions

In this thesis we improve the state of the art in Hybrid Power Systems in several ways. The practical contributions to the field are:

- A Hybrid Power System architecture with only two conversion stages that allows

  - A high wind turbine Power Factor

  - Independent solar and wind Maximum Power Point Tracking

- A software system to control

  - Independent Maximum Power Point Tracking

  - Without solar current sensing or external wind speed sensing

4 HYBRID POWER SYSTEM DESIGN

In this chapter we describe the approach taken to improve Hybrid Power System (HPS) efficiency and reliability. Relevant equations and schematics are described in this chapter, in addition to control system theory.

4.1 HPS Hardware

The proposed HPS consists of only two power electronic stages. The first, a Vienna rectifier, can be controlled to perform Power Factor Correction (PFC) and Maximum Power Point Tracking (MPPT) of a wind turbine. The output of this Vienna rectifier is a DC bus, to which the solar panel is directly connected. The second power electronic stage is a buck converter that pulls power from the DC bus to charge a battery or supply loads. The voltage of the DC bus is varied to allow solar MPPT. This HPS architecture is shown in Figure 4-1, below. In this architecture, the Vienna Rectifier processes power from the wind turbine and the MPPT Converter processes power of both the photovoltaic panels and wind turbine.
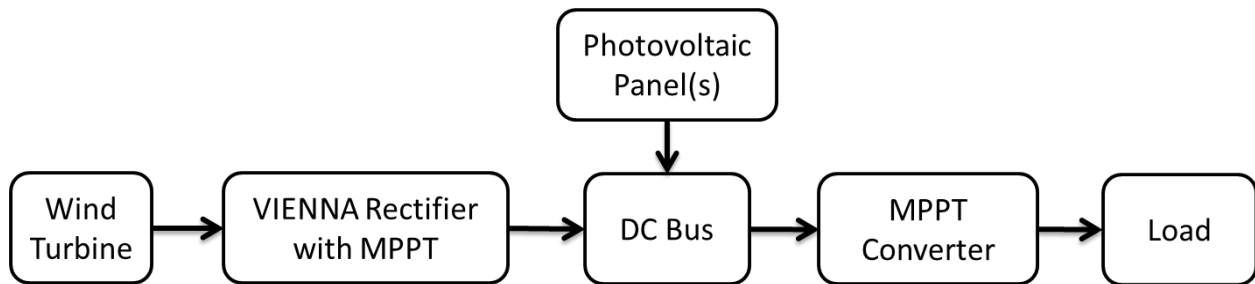

Figure 4-1: Prototype Architecture

4.1.1   Vienna Rectifier

The three-phase AC/DC converter topology used in this project is known as a Vienna rectifier. It
is the combination of three boost converters, one per phase. Precise power control is possible
with these converters. Figure 4-2 is a depiction of a single phase of a Vienna rectifier. The
operating frequency of the power electronics is many times higher than that of the turbine AC, so
the Vienna rectifier can be analyzed for several different DC input cases. The analysis of a
single phase is simple if positive DC input is assumed. This is the case when the AC input is in
its positive half-cycle. The converter operates in two modes. Mode 1 is when both switches are
closed. In this mode, inductor current increases. In Mode 2, the switches are opened and the
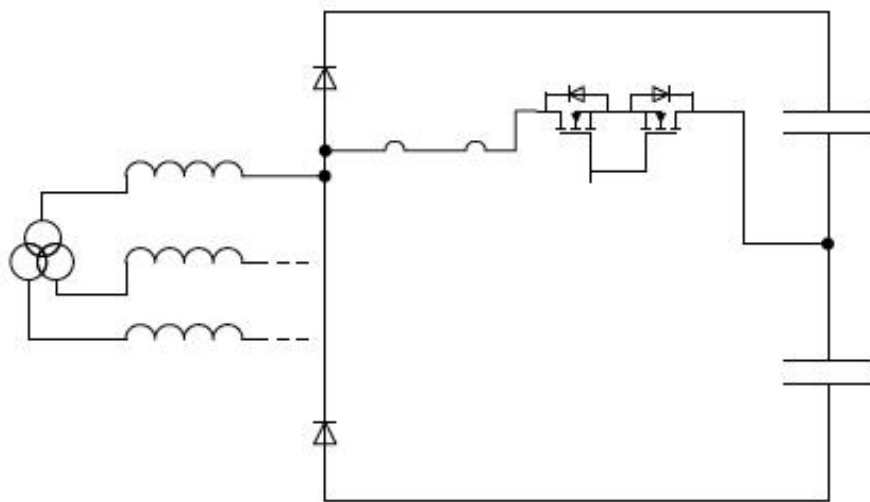inductor current is discharged through the upper diode.

Figure 4-2: Vienna Rectifier topology (One Phase) [Gamboa, 2009]

To analyze the case when the AC input is negative, the same circuit can be analyzed for a
negative DC input. In Mode 1, current increases from the capacitors through the switches and

inductor to the turbine. Mode 2 opens the switches, so current is pulled up through the bottom diodes.

A mathematical model of the Vienna converter is necessary to simulate the HPS. In Gamboa [2009] this has been done with several assumptions to simplify the derivation. These assumptions are that:

- The converter is lossless

- The two stacked bus capacitors (Figure 4-2) have equal voltage

- The input phases are exactly 120 degrees out of phase from each other

- The input phases each provide equal power

- Power from the negative cycle equals the power from the positive cycle for each phase.

The analysis involved augmenting a boost converter model with additional components necessary when the input voltage is negative. In addition to devising a Vienna rectifier model, Gamboa created a wind generator model to simulate the rectifier's operation. The wind generator model approximates the effect of wind speed and loading current (I) on the frequency and amplitude of the voltage output. It produces sine waves for the different phases that are each 120 degrees apart. The turbine model and Vienna Rectifier model are both integral to the control method implemented in this thesis.

4.1.2   Buck Charger

The output of the Vienna rectifier is a DC voltage that is higher than the peaks of the three-phase

AC from the turbine. These peaks, under MPPT, can be higher than 12V. Therefore, it needs to

be reduced to safely charge a battery. The most efficient way to accomplish this is with a

synchronous buck converter. A synchronous buck converter, shown in Figure 4-3, reduces the

input voltage and increases the available current. The two switches work together

complementarily to apply either ground or V_{in} to one side of the inductor. This creates a square

wave at the left side of the inductor. The inductor and capacitor filter and average the square

wave to produce a stable DC voltage proportional to the duty cycle (D) of the top switch (S1).

This topology allows safe and reliable control of power from the DC bus to batteries or loads on

the output. [Batarseh, 2004]
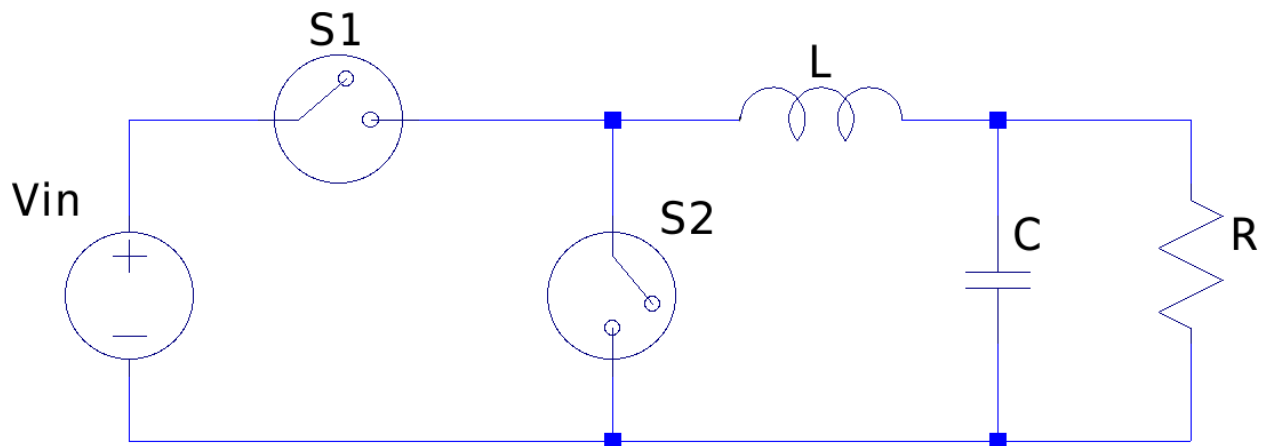
$$V_o = V_{in}D \qquad I_{in} = I_oD$$

Figure 4-3: Buck Converter Topology [Hamilton, 2009]

4.2   HPS Controls

Control algorithms for this HPS are vital to drive the power electronic circuits. There are several interdependent control algorithms that govern the transfer of power in the HPS. These algorithms include Power Factor Correction (PFC), wind Maximum Power Point Tracking (MPPT) and solar MPPT. They each require measurements of voltage and current, which is also discussed in this section.

4.2.1   Power Factor Correction

The PFC algorithm has direct control over the Vienna rectifier. This algorithm must modulate the duty cycle of each rectifier phase independently as the voltage applied to that phase changes. The algorithm discussed in Gamboa [2009] has been selected. This algorithm requires the application of a conductance variable, G. This variable is calculated by the wind MPPT algorithm, which is discussed in the next subsection. This conductance value G is defined as the inverse of the desired resistance of the HPS. This method was designed because making the HPS behave as a resistor would produce a perfect power factor. This PFC algorithm requires the measurement of I_{in} and V_{in}, while relying on the assumption that the bus voltage does not fluctuate. Figure 4-4 shows how the measurements and calculated variables are implemented in the PFC algorithm. The conductance, G, is multiplied by the instantaneous input voltage. The difference between resulting desired current, I_{ref}, and the instantaneous current, I_{in}, is fed to a compensated controller that manipulates the duty cycle of a rectifier phase. This control system runs concurrently for the three phases to simulate a resistive load on the turbine.
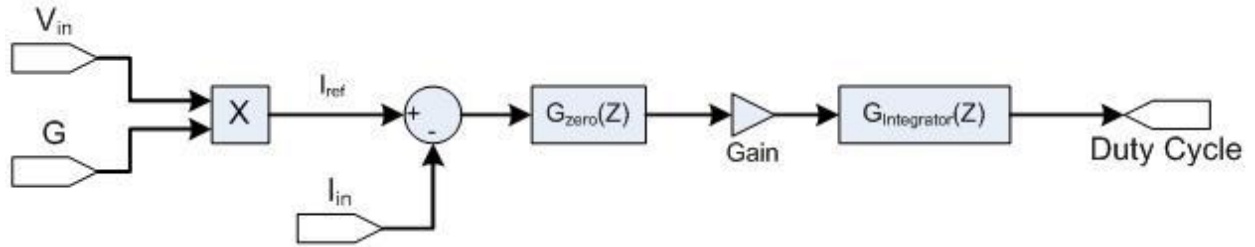
Figure 4-4: Conductance (G) PFC Algorithm [Gamboa, 2009]

Outside of the PFC control loop, certain safety measures must be in place. To protect the DC bus from high voltage, the rectifier duty cycle must be limited when the bus rises above certain levels. This limit is integral to the method of battery charging, which is discussed in detail in a later section.

4.2.2   Wind Maximum Power Point Tracking

Wind MPPT calculates a desired conductance, G, based on the previous and current power level. It follows a simple hill-climbing method of power point tracking. It relies upon measuring the peak voltage and current. To conserve microprocessor resources, it is assumed that the three phases have equal amounts of power available. This assumption allows a single conductance variable to be created, rather than a unique conductance per phase.

The wind turbine is a mechanical system with momentum. Therefore variations in wind power occur slowly. This requires the MPPT controller to be much slower than the PFC controller. Their speed difference allows the PFC controller to find the local maximum of both I_{in} and V_{in}. The PFC controller measures both I_{in} and V_{in}, the two parameters necessary for MPPT, and stores them. On subsequent iterations, the PFC controller measures them again, compares the current value to the stored one, and stores the highest value. The values must be reset to zero if

the conductance value is changed. The MPPT controller uses the peak value and the peak value from its previous iteration to calculate the desired conductance G.

This MPPT algorithm is able to find the maximum power point of a wind turbine without external wind sensors. Additionally, it is independent of the bus voltage and battery current. This independence is necessary to allow solar MPPT.

4.2.3   *Solar Maximum Power Point Tracking*

Solar MPPT is crucial for extracting the maximum power under varying solar radiation intensities. It is typically accomplished by varying the voltage and current of a solar array, converging at a maximum power point. Within this HPS, the solar array is directly connected to the DC bus. This raises complications because of the boost nature of the Vienna rectifier and the buck charger. In order to supply maximum power, the solar array Maximum Power Point Voltage (V_{mpp}) must be greater than the battery voltage. In addition, it must be higher than the Vienna input. An obvious weakness to this method is poor power extraction under low solar radiation. This sacrifice has been made to keep size minimal and efficiency high.

The solar MPPT algorithm uses current sensing through the buck converter and Vienna rectifier only. Scaling factors and subtraction of the rectifier peak current from the total buck current can yield solar current. These measurements and calculations can be combined with the bus voltage and use a basic hill-climbing algorithm for solar MPPT.

4.2.4   Alternate Maximum Power Point Tracking

Signal integrity and electrical noise may make the previous method impractical and virtually impossible. The generator voltage is highly variable. Under low wind conditions, it may be as low as 4V peak-to-peak, but still be able to provide significant power. At such low voltages, signal noise may render the previous MPPT method unusable. Therefore, an alternate algorithm may be required.

Such an algorithm should function without use of the Vienna current or voltage sensing. This can be accomplished by alternating wind and solar MPPT. They both will be measured and tracked using the power output of the buck converter. Because the buck output is connected to a large battery, the voltage will remain nearly constant, and the current can be measured and used as an accurate power measurement.
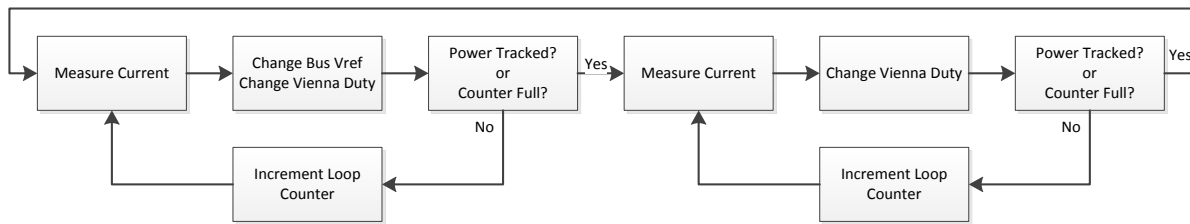

Figure 4-5: Alternate Hybrid MPPT Algorithm

This algorithm, presented in Figure 4-5, relies on speed to maintain stability. Under slowly-changing conditions this algorithm can easily work, but only real-world testing can verify its viability for a HPS.

4.2.5 Battery Charging

Battery charging and protection is crucial to extend the life of a battery, and to prevent dangerous overcharging. This HPS is designed to use lead acid batteries because of their good capacity, affordability, and ease of use. Their weight and large size are unimportant because the HPS is intended to be stationary. The HPS controls were designed to protect the battery from being overcharged. Over-discharge protection must be offered by a separate load controller.

Lead acid charging is commonly controlled in three stages. The first stage is characterized by constant current. It supplies the battery with a high current and causes the voltage to rise. The second, characterized by constant voltage, gradually reduces the charging current as the open-circuit battery voltage increases. The final stage is an indefinite float charge. This stage applies a constant voltage with low current to maintain the battery over extended periods of time.

These stages are intended for charging a battery from a plentiful supply, such as a car alternator or utility grid. When supplied by limited renewable sources, the different charge stages are treated as limits. For example, the constant current stage is a current limit stage. The HPS will push as much current to the battery as possible as long as the current is less than the current limit. Similarly, the constant voltage stage is controlled by both a voltage limit and a current limit. The current limit is the same as in the first stage, but an additional voltage limit is imposed. The third and final stage is implemented as a different voltage limit and a much lower current limit. The charging algorithm can move freely between the first two stages as the battery voltage commands. This would occur if there was a load in addition to the battery.

4.3   Hybrid Power System Design Summary

This chapter discussed the topologies, architectures, and control rules implemented in this thesis. These particular ideas have been combined to create a series-architecture HPS that is able to extract maximum power from a wind generator and from a solar panel simultaneously. The next chapter discusses the creation, simulation, and testing of a HPS. Later chapters discuss the results, conclusions, and future studies as a result of this thesis.

5   HYBRID POWER SYSTEM SIMULATION

Simulations are frequently used to test both the hardware and software of power electronic converters. They can be conducted to predict the efficiency of a power converter, or to test an experimental control system. They allow tests that might be time consuming to set up, or even tests that would damage the power electronics or endanger test equipment.

This thesis focuses on novel control algorithms on established hardware, therefore simulations have been conducted to test control systems and predict the response to changing wind and solar intensity. The final simulation to test the Hybrid Power System control system was assembled in components, the output buck converter, battery, solar panel, input Vienna converter, and wind turbine. Each part was created and simulated separately, then combined into the complete model. This chapter describes those simulations, the results obtained, and the conclusions drawn from the results of those simulations.

5.1   HPS Simulated Architecture

The full HPS simulation should be capable of testing all different cases of the real-world HPS, such as:

- No wind, variable solar intensity

- Static wind, variable solar intensity

- No sun, variable wind speed

- Static sun, variable wind speed

- Variable wind speed, variable solar intensity

The models of the HPS were developed in Matlab Simulink. The architecture is shown in Figure 5-1. Each of the components was designed to interact with a common central capacitor, Output Stage_Capacitor2. This bus capacitance is situated between the Vienna rectifier and the buck converter. The rectifier, solar panel, and buck converter each receive a voltage signal from the bus capacitance and calculate their current draw from that capacitor. This allows each of the components to be used separately with the capacitor, and all together with no change in functionality.
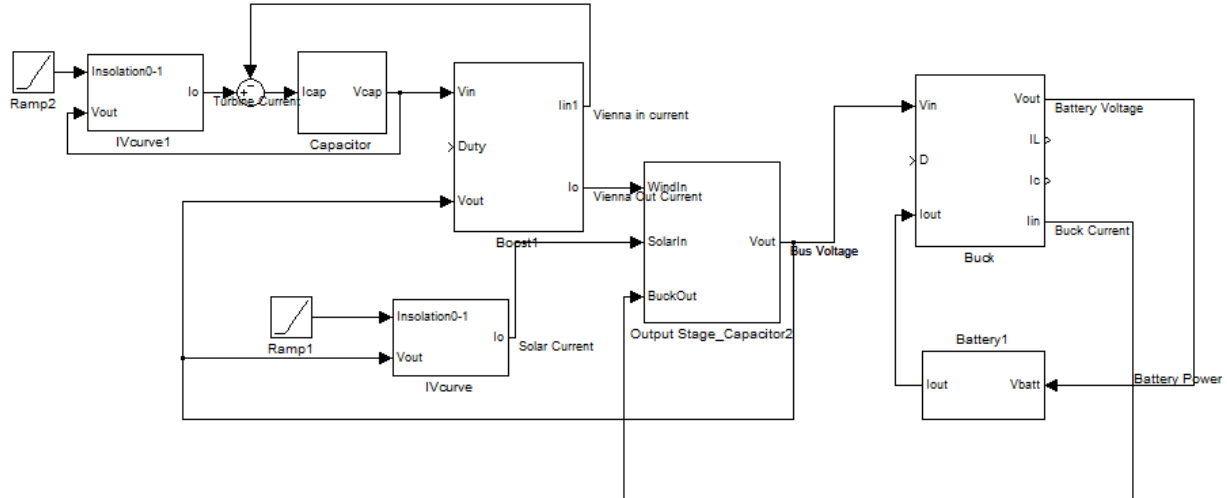

Figure 5-1: HPS architecture in Matlab Simulation

5.2 Solar Simulation

Simulating a HPS required the creation of a solar panel model that could apply to the HPS architecture. The solar panel power point must be controllable, and a voltage input must produce

a specific current output. Therefore, a solar panel model was created to have a certain IV (current to voltage) curve that is scaled by the intensity of solar radiation. First, this model was verified by plotting the output over the whole range of inputs. The model chosen is a simple linearization of the standard IV curve. It includes two lines that intersect at the maximum power point. One line, from the short circuit condition to the maximum power point, models a slight decline in current over a large rise in voltage. The other line, from the maximum power point to the open circuit voltage, depicts a large decline in current over a small rise in voltage. Once the model was sufficiently refined, basic MPPT testing was performed. This testing, shown in Figure 5-2, tested an MPPT controller changing the Buck Current. The Buck Current is manipulated, and the Solar Power is monitored. This proves that the power point of this solar source can be manipulated and observed and is appropriate to simulate a Hybrid Power System.
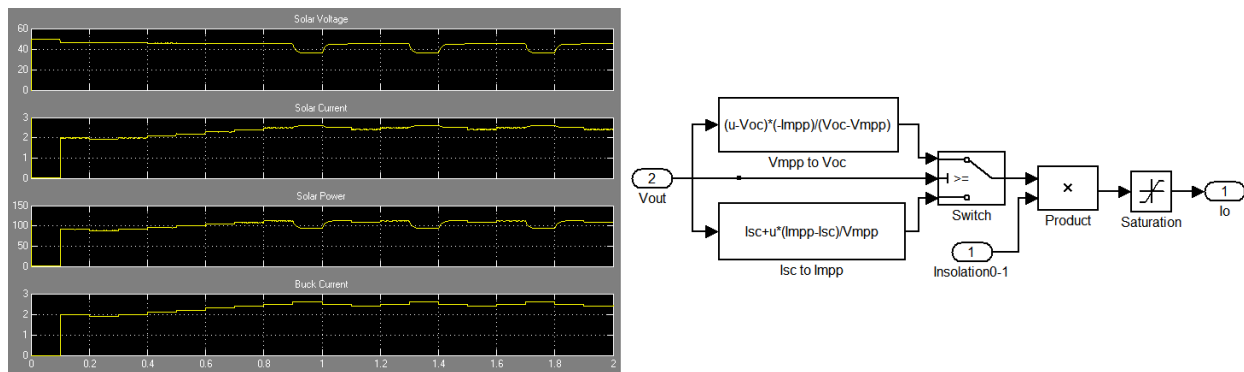

Figure 5-2: Simulated Solar MPPT (left) and Solar Panel Model (right)

5.3   Wind Simulation

Similar to the solar panel, a wind turbine model must be created to simulate a HPS. An ideal wind turbine model for this experiment consists of a three phase generator and Vienna rectifier. The three phase generator must produce a certain IV curve when provided with a wind speed.

The Vienna rectifier controls the power point on the IV curve by manipulating the duty cycle and

bus capacitor voltage. An ideal model was produced, but it proved to be too computationally

difficult and a simpler model was desired. The simple wind model must accurately model the

DC current output, controlled by wind intensity, duty cycle, and bus capacitor voltage. This

model incorporates an IV curve similar to the solar curve, but with slower response time. Inside

the simple wind model is a DC turbine and a boost converter. This simplification reduced the

number and complexity of several calculations without losing the controllability of the wind

source. Any lost detail is unnecessary in an MPPT simulation, but would be crucial when

simulating the topology for efficiency or electrical performance.

In the test simulation, a wind turbine under constant wind conditions has its maximum power

point tracked. Figure 5-3 Shows the model used in this testing. As described in the previous

paragraph, it includes a DC turbine and boost converter, connected to the output capacitor. This

model includes provisions for the buck converter and solar panel, so it has been used at the
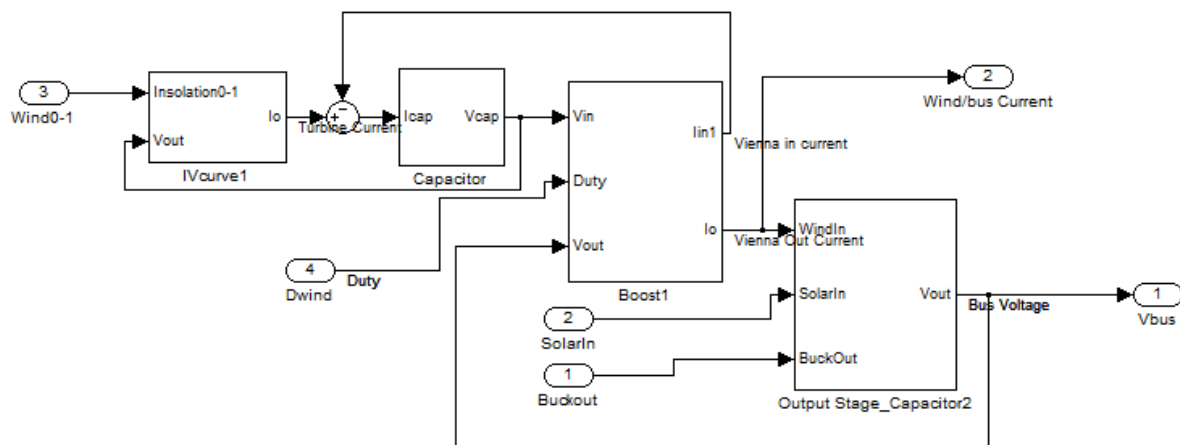
starting point for developing the full HPS model.

Figure 5-3: Wind Turbine Model

Testing this model yielded satisfactory MPPT measuring current and controlling wind duty cycle. The results of this simulation are shown in Figure 5-4. The wind turbine was provided with a constant wind source, and an MPPT algorithm changed the duty cycle to ensure maximum power output. In this figure, the turbine voltage oscillates around 25V, which is the maximum power point. Therefore, this wind model is able to model a wind turbine with a measurable and trackable maximum power point.
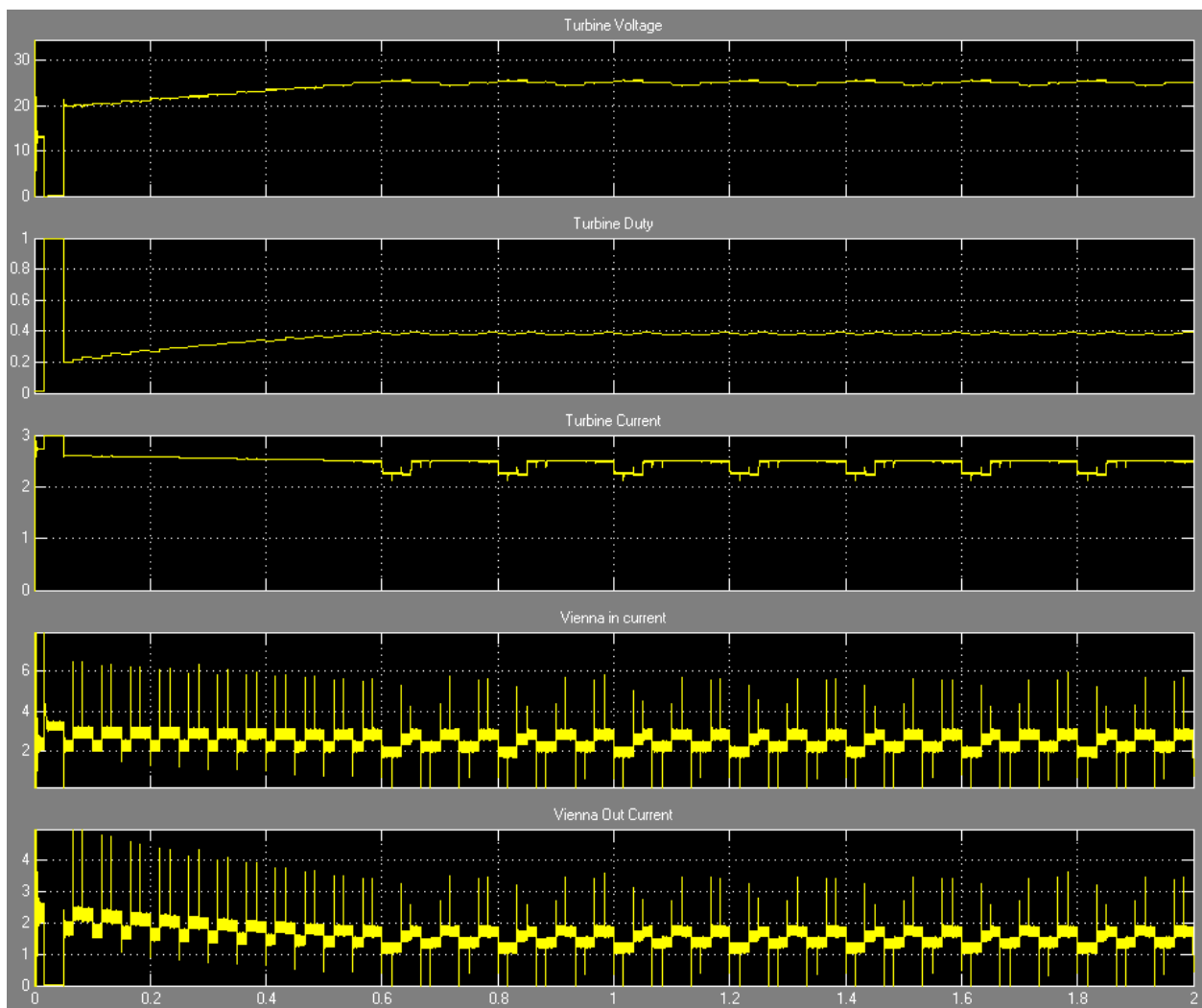

Figure 5-4: Wind only MPPT Simulation

5.4   Hybrid Simulation

Simulating the whole HPS is an efficient and safe way to test different control systems. As it has been explained in the previous sections, the HPS model was developed in pieces with Simulink. First a solar model was created then tested. Next, a wind turbine model was developed from the solar model and tested through a variety of cases.

The HPS model, shown below in Figure 5-5, consists of a central bus capacitor with inputs for wind, solar, and buck current. In addition, there is a bus voltage output. This capacitor must have balanced currents on the input if the voltage is to remain stable.
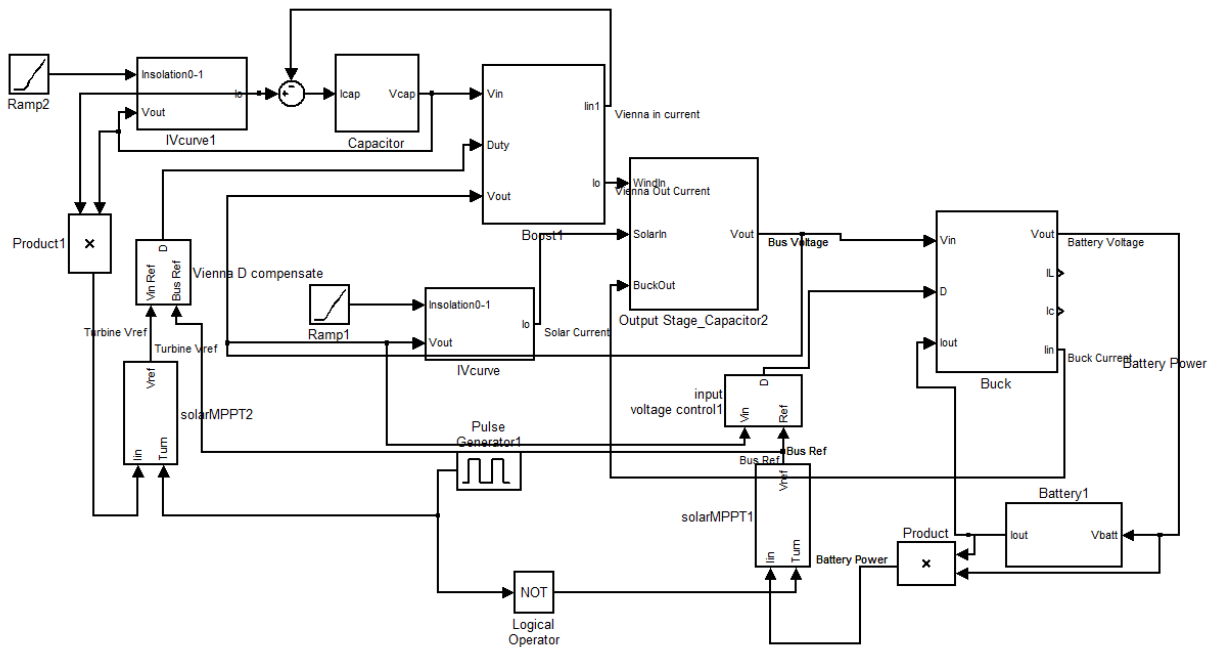

Figure 5-5: Hybrid Power System Simulink Model

The HPS model incorporates two control systems. One is the wind MPPT, and the other is solar.

Each calculates a desired voltage for the renewable source, and then a simple calculation yields

the duty cycle to obtain that voltage. The Vienna calculation yields a theoretical DC voltage, such as would be produced by a DC turbine. However, in a three-phase situation that voltage is approximately the RMS value. In the physical converter, additional controllers must be in place to protect the battery and converter.

The maximum power points of the two renewable sources need to be individually tracked. Two different methods of tracking were presented in section 4.2. The first method tracks the two sources concurrently, and the second alternates between the two sources. The first method is expected to find the maximum power points faster, but to be more susceptible to noise and interference. The second method is expected to be slower, but more robust. These two methods both should be proven through simulation before they get tested on hardware to attain an accurate conclusion.

As explained in section 5.1, there are numerous tests to be performed on this HPS model before moving to the physical HPS. These tests are intended to verify the performance of the HPS control system in real-world situations where the two renewable energy sources are highly variable.

5.5 Simulated Results

This section discusses the specific simulations that the HPS model has been run through and the results obtained.

5.5.1   *Static wind speed, static solar intensity*

This first combined test shows that the converter can find the maximum power point of both

sources. This test is shown in Figure 5-6. The solar maximum power point, 45V, is shown in

the 'Bus Voltage' graph. The graph reaches 45V at 1.5s. The wind maximum power point, 25V

is shown in the 'Turbine Voltage' graph. It reaches the maximum power point earlier, at 1s. It is

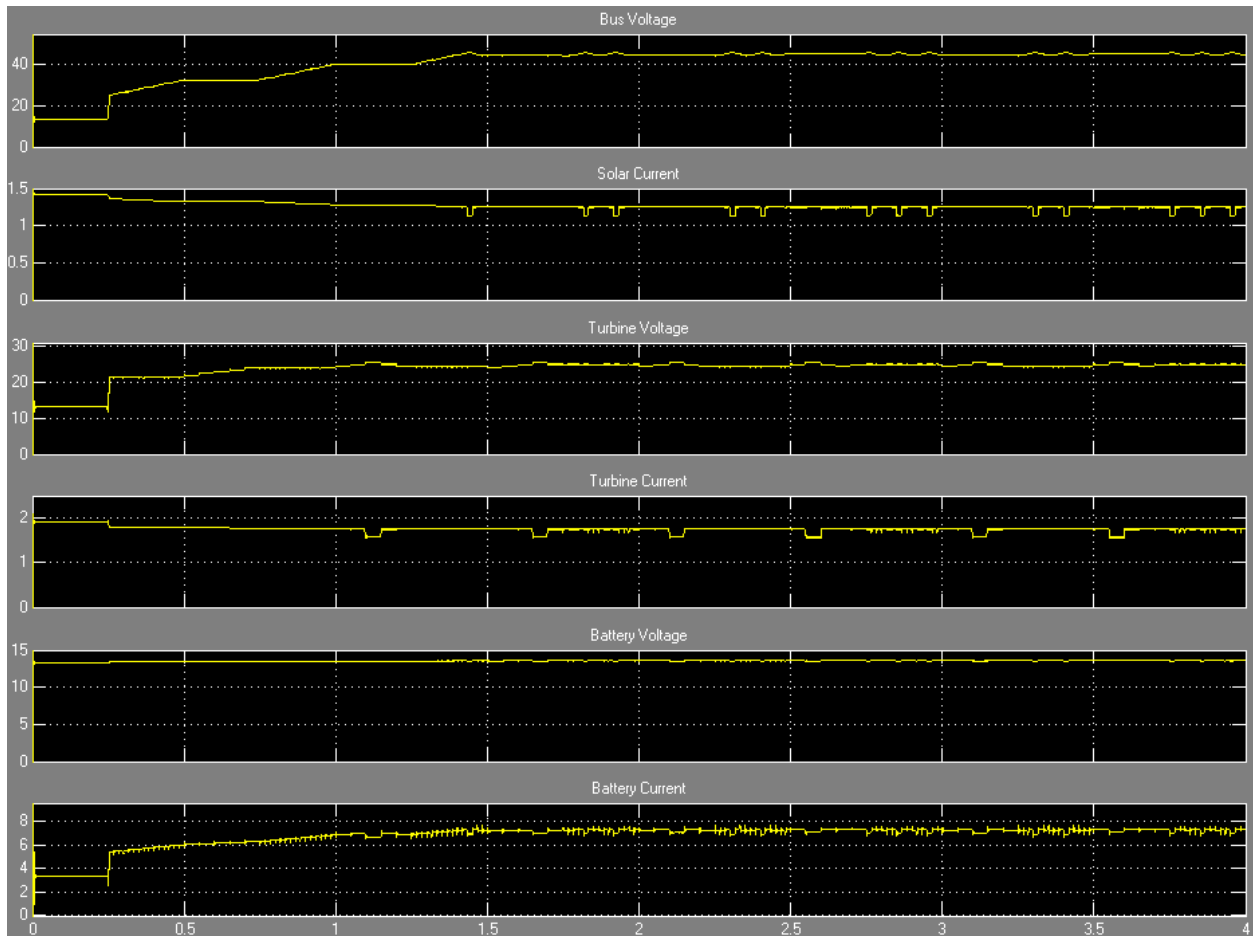faster because the initial voltage was much closer to the maximum power point.

Figure 5-6: Static wind speed, static solar intensity

5.5.2   No wind, variable solar intensity

In this simulation circumstance the wind intensity was maintained at zero and the solar intensity was rapidly increased at t=2.0s. After the rapid change in solar intensity, this model takes approximately 0.1s to find the new maximum power point.

Figure 5-7: No wind, solar increase at 2.0s

5.5.3 Static wind, variable solar intensity

In this simulation the wind intensity was maintained at 0.5 and the solar intensity was rapidly increased at t=2.0s. After the rapid change in solar intensity, this model t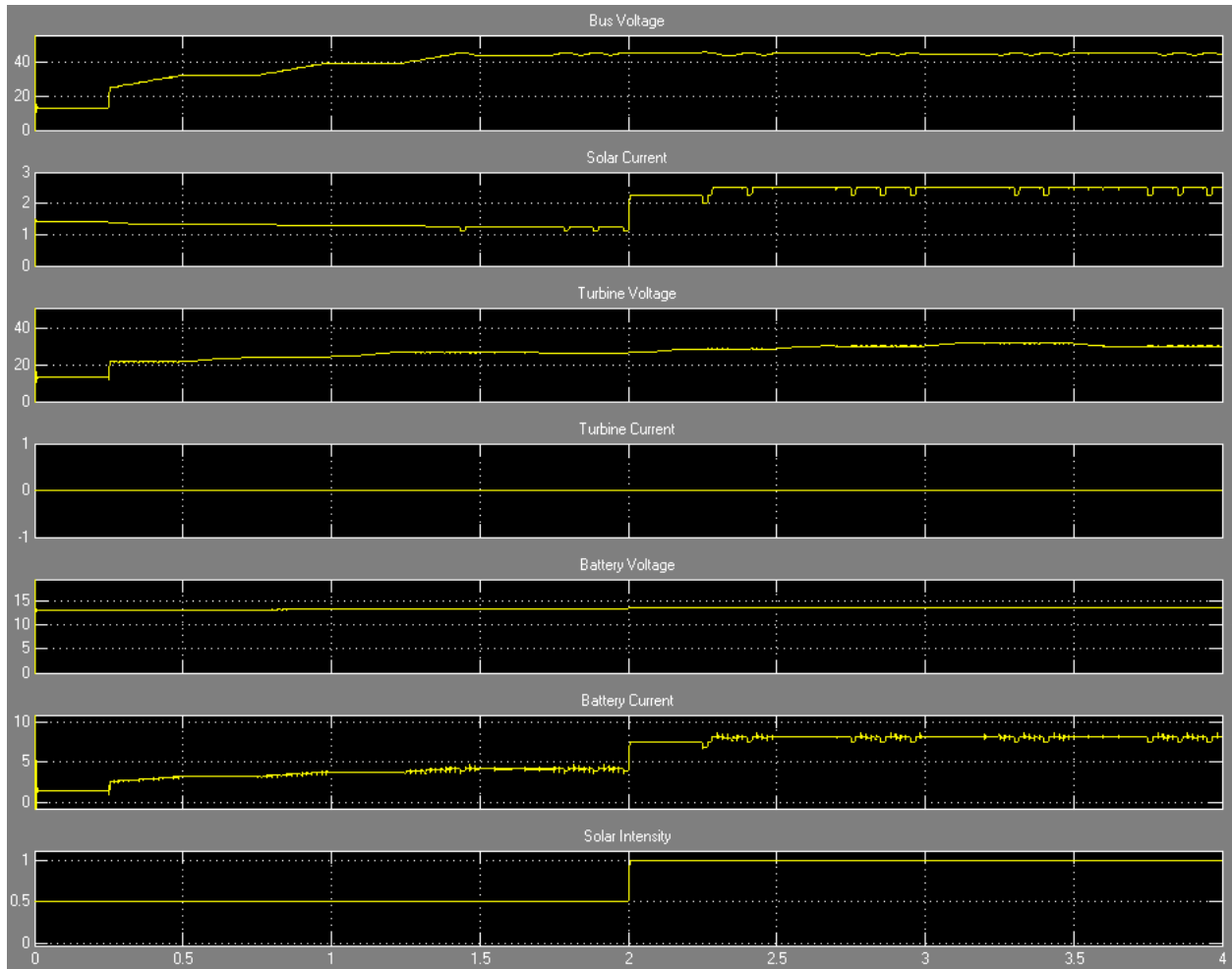akes approximately 0.1s to find the new maximum power point. This shows no change in response over the previous simulation.
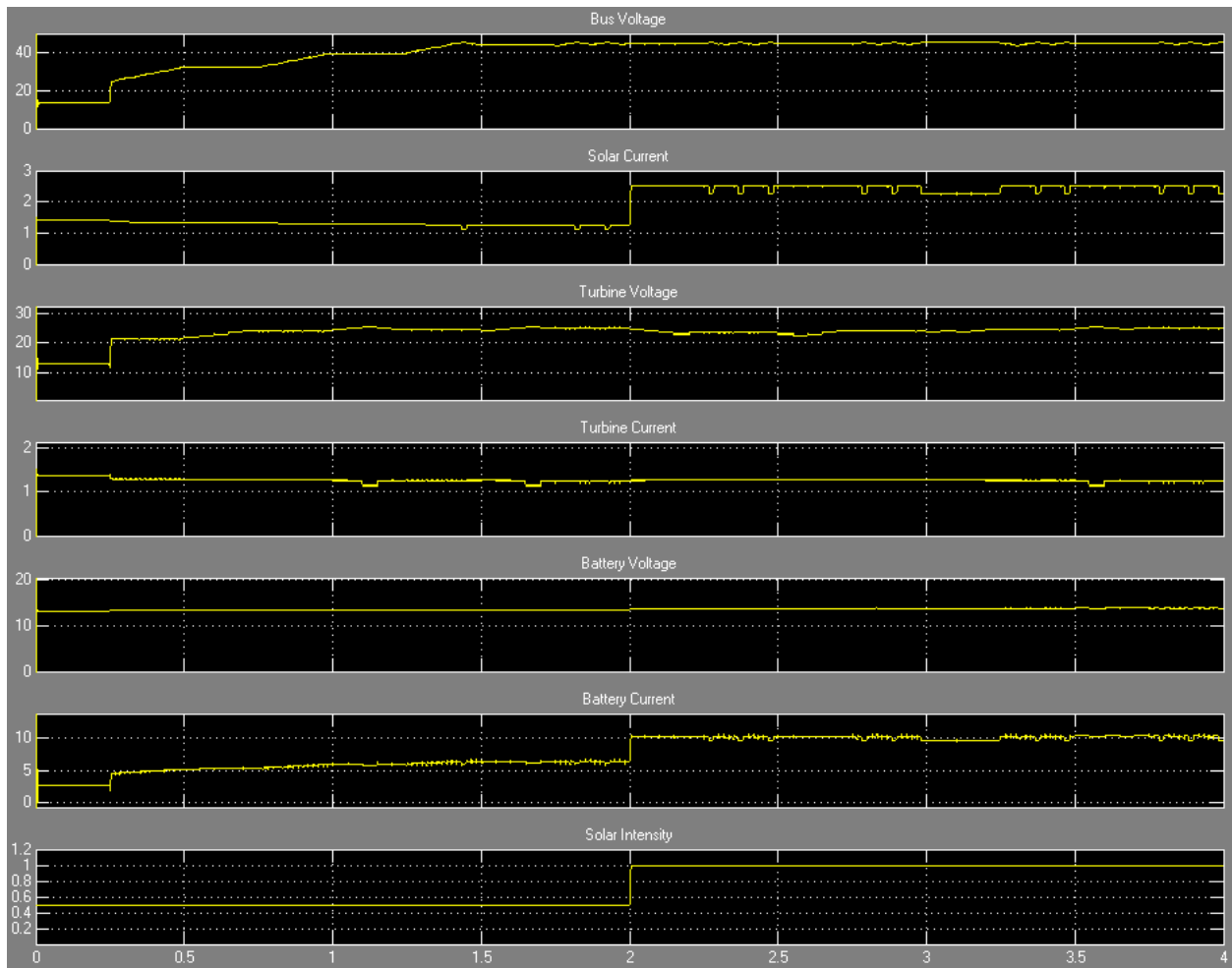

Figure 5-8: Static wind, solar increase at 2.0s

5.5.4 No sun, variable wind speed

This simulation demonstrates wind MPPT under a zero sun situation. This would be the case if the wind increases at night. As can be seen in the turbine current and voltage, it takes just over 0.1s to stabilize after the intensity increase. In this simulation, the bus voltage was oscillating despite not having and solar power available. This allows the converter to track a solar source as soon as one becomes available.
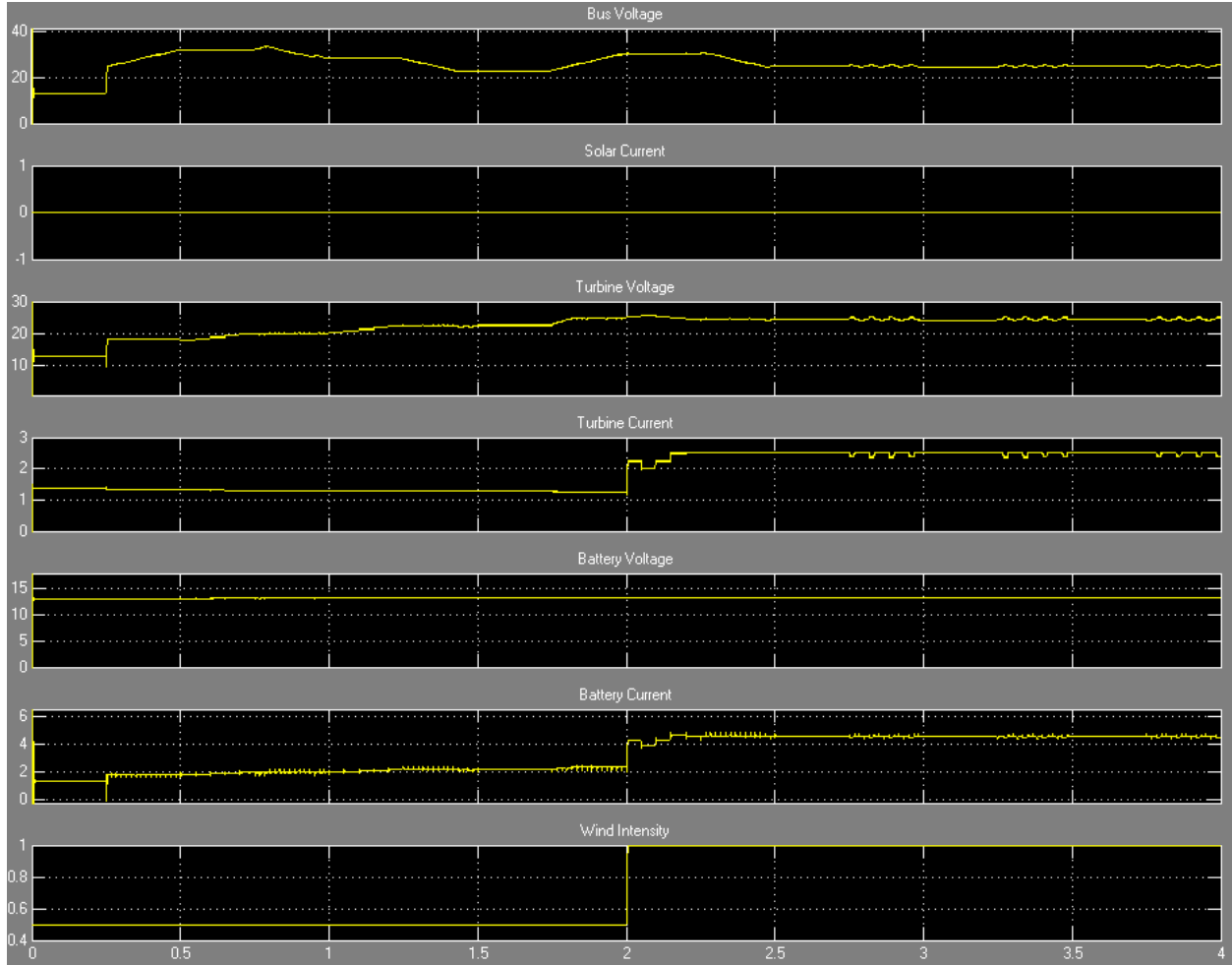

Figure 5-9: No sun, wind increase at 2.0s

5.5.5 Static sun, variable wind speed

In this simulation, the solar intensity was held constant and the wind was increased at 2.0s. Just like in the previous example, the turbine takes just over 0.1s to stabilize. This can be seen in the turbine voltage. Unlike the previous simulation, the bus voltage was used to find the solar maximum power point.
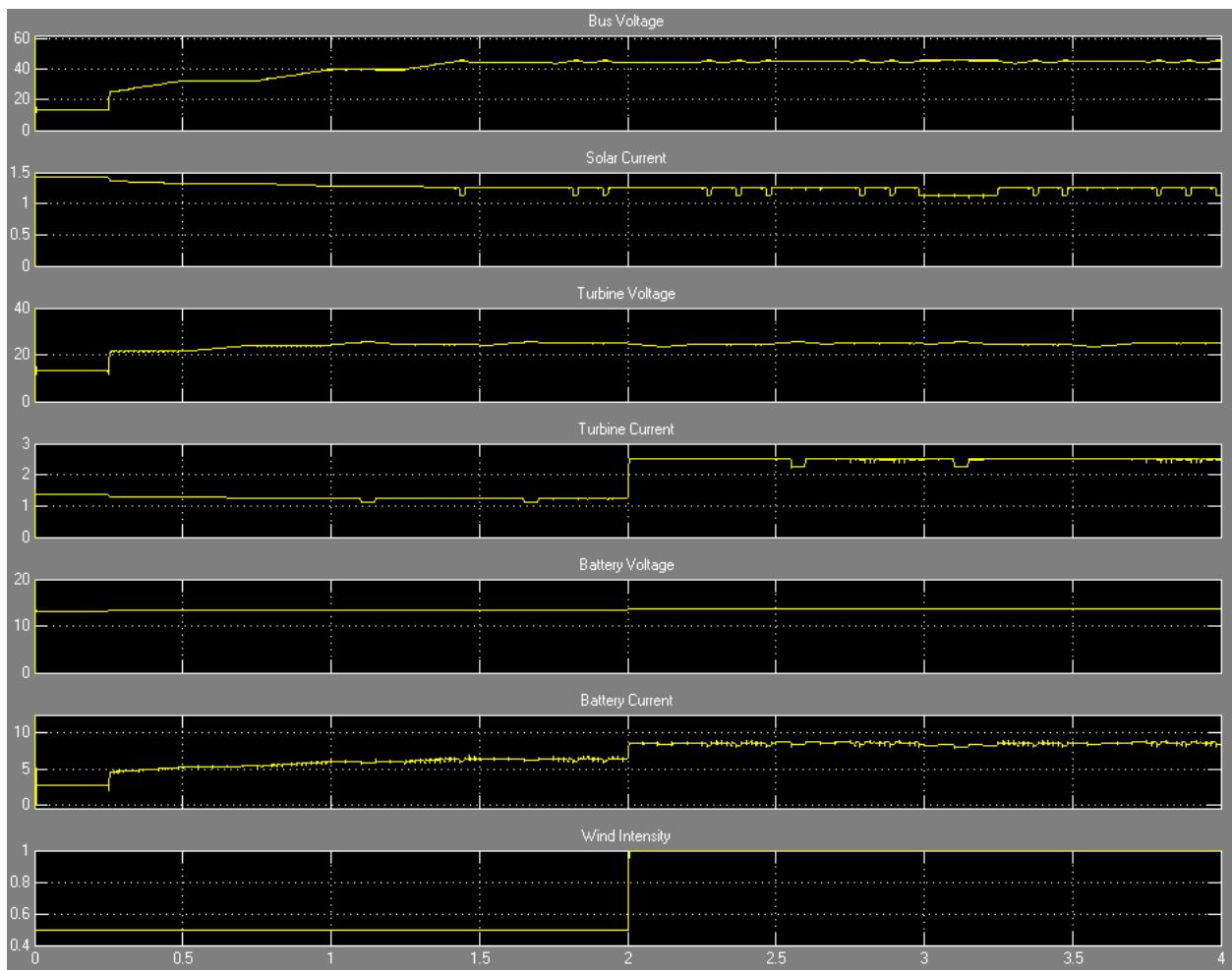

Figure 5-10: Static sun, wind increase at 2.0s

5.5.6 *Variable wind speed, variable solar intensity*

This next simulation shows the system with rapidly changing wind and solar intensity. Each
source was supplied by a square wave, going from zero to maximum intensity rapidly. The
inputs are shown on the bottom two lines of the graph. This demonstrates MPPT that converges
rapidly, but both power points are affected when either source was changed. Also, it is apparent
when the solar power point changes, like from 7 to 8 seconds, that alternating between the
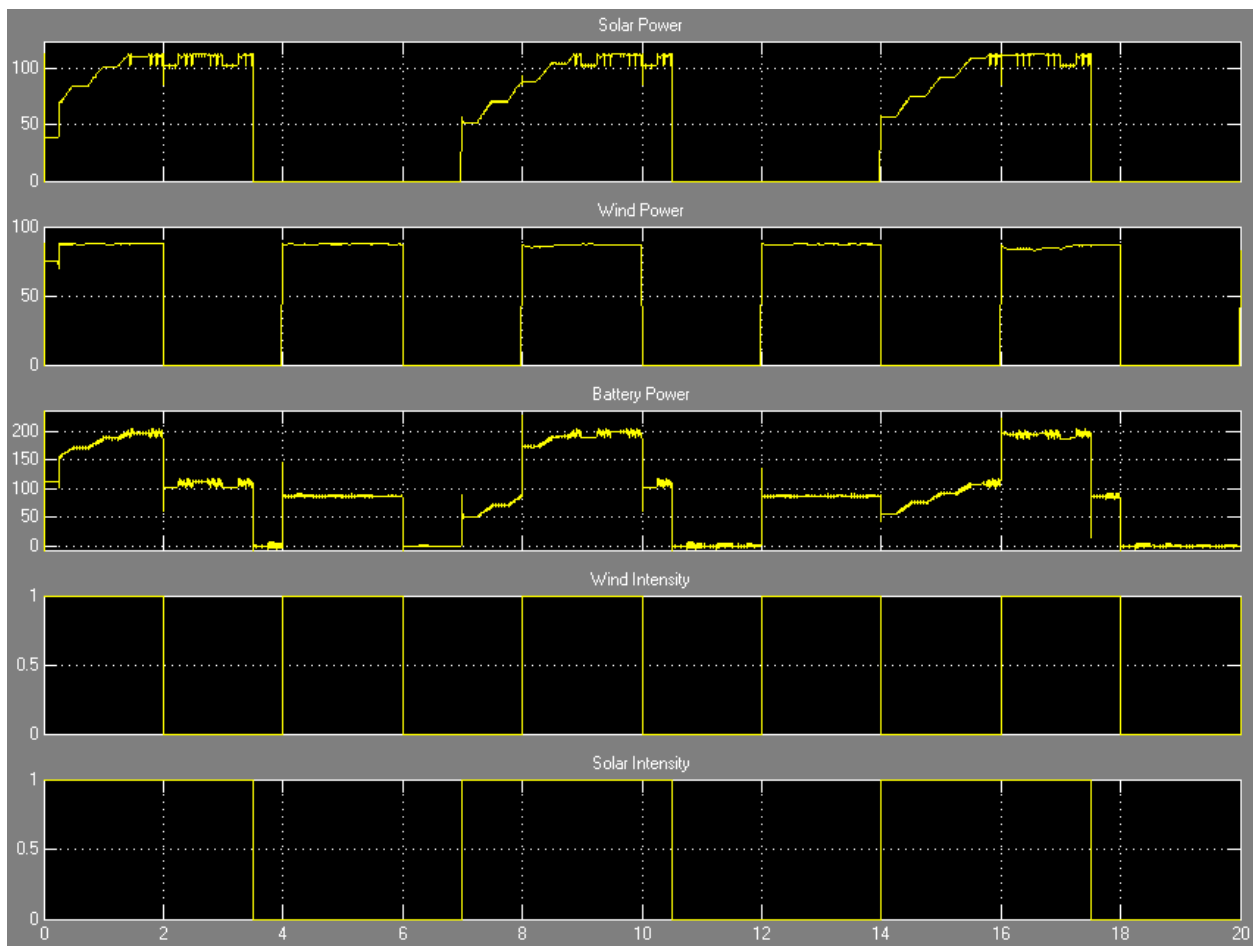sources slows down the algorithm greatly.

Figure 5-11: Both sources vary, Battery current MPPT method

5.5.7 Variable wind speed, variable solar intensity Simultaneous MPPT

This simulation has the same input as the previous one, but it demonstrates a different method of MPPT. All simulations up to this point have used the battery current as the sole measure of power. Both solar and wind maximum power point tracking relies upon the output current. Because of this, changing one source would interfere with the measurements of the other. Therefore, the tracking must alternate.

This algorithm demonstrates an alternative that uses the Vienna output current to track the wind turbine maximum power point. The solar power point was tracked by calculating the difference between battery current and Vienna current. These currents are not directly equitable, so they must be scaled first. The Vienna current goes directly into the bus, so it is at the same voltage as the solar current and needs no scaling. The battery current is at a different voltage, so must be scaled by the buck duty cycle.

$$I_{solar} = D_{buck} * I_{battery} - I_{Vienna}$$

In order to be a measure of power, the solar current must be multiplied by the solar, or bus, voltage. This results in two multiply operations. To reduce calculations, solar MPPT will be based off of the solar component of battery current, calculated by the following equation.

$$I_{solarbatt} = I_{batttotal} - I_{viennabatt} \Rightarrow I_{solarbatt} = I_{batttotal} - \frac{I_{Vienna}}{D_{buck}}$$

The results of this simulation, shown in Figure 5-12, display faster convergence times for the solar power. Wind power appears to take longer randomly. The first and third startups have nearly instantaneous MPPT. It appears that the algorithm stumbled upon the correct value. The rest of the startups have much longer convergence times. This is especially true for the last startup.
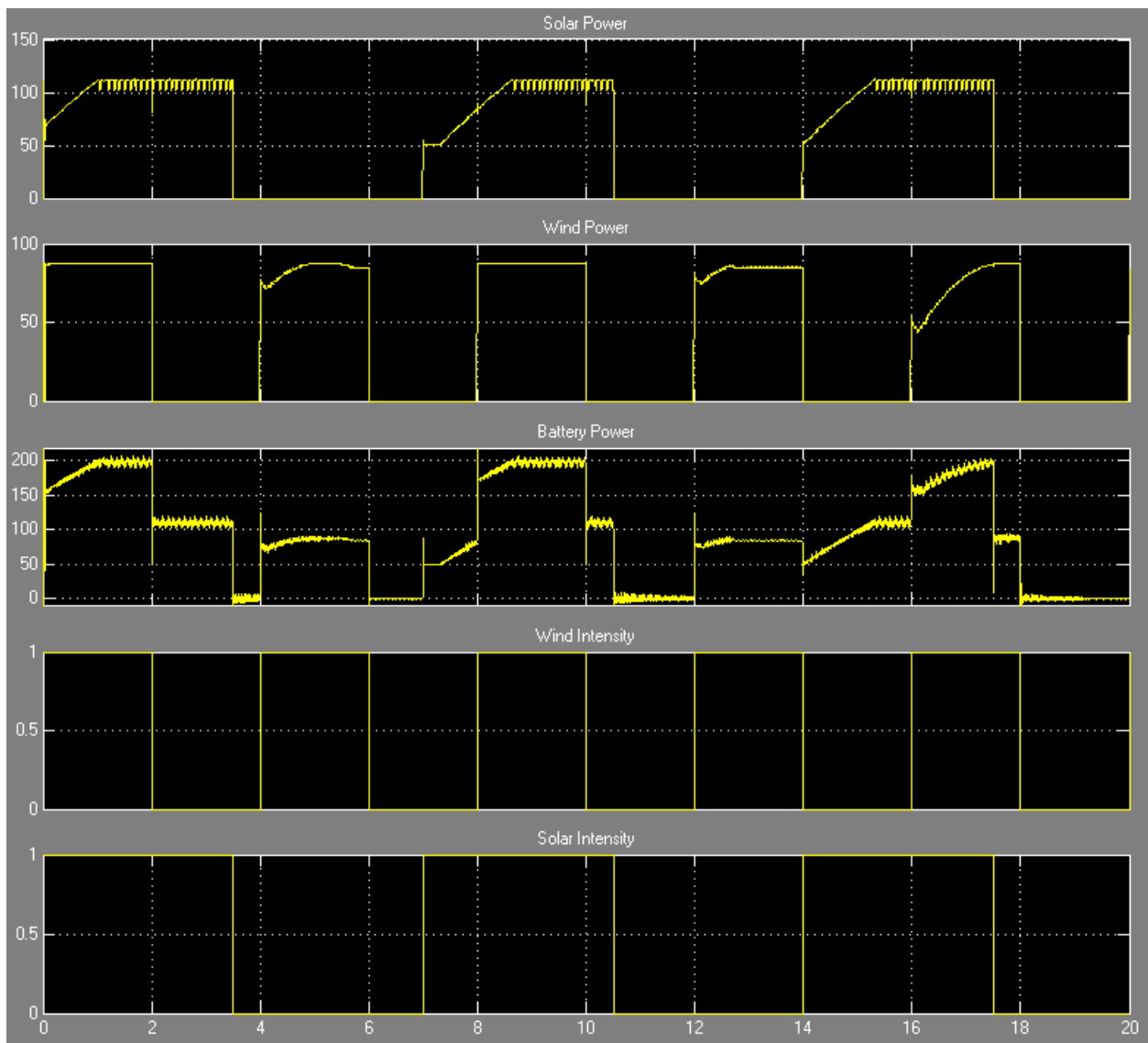

Figure 5-12: Both sources vary, Simultaneous MPPT method

5.6   Simulation Conclusion

These simulations produced results as expected. They aided in the development of the HPS control system by exposing calculation difficulty and the overlooked requirement of scaling current measurements by their voltage to provide a power measurement.

The alternating and simultaneous MPPT tests have showed that both would be able to track the two sources independently. Hardware testing of the two algorithms will show whether each algorithm is viable in a real-world situation. In hardware testing, the algorithms will have to cope with sensing noise and component limitations.

After the HPS prototype was created and tested, a limitation of this simulation was brought to the attention of the researchers. The maximum power point of the IV curve does not change voltage when the solar or wind intensity changes. Only the output current is modified. In an ideal system both the maximum power voltage and current would change. The simplicity of each MPPT algorithm means that they are not affected by this limited simulation, but a more complicated MPPT algorithm could face difficulty by using this IV curve.

6 HYBRID POWER SYSTEM PROTOTYPE

The prototype Hybrid Power System developed for this research was designed to be small, efficient, and inexpensive. This prototype HPS development can be divided into two broad categories, hardware and software. These categories can each be divided to describe the individual systems involved, and what systems have been incorporated from previous research. This chapter describes the design of this prototype HPS separated into hardware, software, and the associated subsystems.

6.1 Hardware

This HPS is intended to be small and inexpensive. As a result, the prototype has been designed to weigh less than 3 kilograms and have less than 2 liter volume. These requirements were set for the 2009 Future Energy Challenge for a Wind Turbine Energy Maximizer, and will be adhered to for this prototype HPS [IEEE, 2008]. This section describes the design of the hardware subsystems.

6.1.1 Wind Prototype Hardware

An existing wind turbine energy maximizer will be used for this research. The existing energy maximizing power converter was developed by Hamilton [2009] and Gamboa [2009]. This converter competed in the 2009 Future Energy Challenge (FEC) and attained 93% efficiency. They implemented a three-phase Vienna rectifier cascaded with a synchronous buck converter. These two power stages are described in this section.

Because the small wind turbine in this project produces three-phase AC, a three-phase Vienna converter was built. This component of the converter was designed for the 2009 FEC, and was rated for 300 Watts of continuous power, 900 Watts peak power. The Vienna phases individually only have to convert 100 Watts of continuous power or briefly 300 Watts. When designing the wind converter, the DC bus between the two power stages was expected to remain constant at 40V. Because of this, the Vienna phase current was expected to not exceed 15A. Therefore, relatively small switches and inductors were selected. In the proposed topology, solar MPPT depends upon a variable bus voltage. This will change the current requirements for the Vienna phases. However, as will be discussed in Chapter 7, the selected solar panel cannot supply more than 100 Watts and the wind turbine less than 300 Watts, so the component ratings will be more than adequate.

A buck converter that regulates the output power to safely charge a battery was also incorporated into the 2009 FEC design. This buck converter was designed for 300 Watts continuous, 900 Watts peak. However, in the prototype HPS, the buck converter must process power from solar and wind sources. The FEC 2009 buck converter was deemed sufficient to test the new control system, but the total system power has been limited to 300W during testing. This was limited at the wind and solar inputs.

Current sensing is performed on each of the Vienna phases and on the buck output. Low value 'sense' resistors have been selected. The potential difference across these resistors is amplified with a differential amplifier and then sampled by an analog to digital converter built into the microcontroller. These precise measuring circuits require many components and precise

calibration. However, their low component cost and small size make them an integral part of this design. Still, their use should be minimized to reduce the production cost of a HPS. Therefore, a decision was made to not have a dedicated current sense circuit on the solar input. The difference between the Vienna power measurement and the buck power measurement is ideally the solar current. This information will need to be filtered and scaled to calculate usable solar current data.

Solar power can be added to the FEC 2009 converter with very few components. The solar panel is directly connected to the DC bus between the Vienna rectifier and buck converter. There are no new power stages.

6.2   Software

The software running on the onboard microcontroller, a Microchip dsPIC30F2023, can be divided into several components. The first contains all of the setup functions and registers. These will not be discussed in detail, but important variables will be explained where they are used in the software structure. However, the different speed of control algorithms will be discussed.

6.2.1   Software Structure

The software structure can be divided into slow and fast control loops. The fast loops are triggered to run every four switching cycles. The switching frequency is 50kHz, so the fast loop runs at approximately 12.5kHz. The fast loop takes measurements so that they can be filtered.

The slow loop is allowed to run every 45 milliseconds, so at approximately 22Hz. The slow loop contains the wind and solar MPPT algorithms. This must run slowly to allow the sources to adjust after a change in power draw. Time constants associated with the solar array are long, and the turbine even longer.

6.2.2   Fast Loop Controls

The fast loop is triggered by the switching frequency (50 kHz), but is only allowed to run on every 4th interrupt. Therefore it runs at 12.5 kHz. It is forced to run relatively slowly so the microcontroller has time to perform the necessary calculations. It may need to be further slowed down to accommodate the more complicated peak-current measurement. This loop measures the associated currents and voltages. In addition, it filters the current and voltage values to improve the accuracy. Peak current is measured to obtain the local maximum current on a Vienna phase, while peak voltage is measured to obtain the local maximum voltage.

The peak measurements are performed on only one phase to conserve processor cycles. This relies on the assumption that the power is linearly proportional between the three phases. In other words, the ratio of phase one to phase two to phase three power is constant. This is portrayed by the following relationship, where P is phase power, C is a phase proportionality constant, and U is a power scalar that varies with wind and current draw.

$$P_1 : P_2 : P_3 = (C_1 : C_2 : C_3)U$$

That assumption allows MPPT to be run on any one phase and the other phases will sympathetically be run at their maximum power point. The peak voltage and current for a phase are measured by comparing a stored value to a recently measured value and storing the larger one. These variables are reset every iteration of the wind MPPT algorithm.

6.2.3   Slow Loop Controls, Simultaneous MPPT

Control algorithms in the slow loop are allowed to run every 45 milliseconds. The slow control algorithms include solar MPPT, wind MPPT, and battery charging. These functions benefit from filtered measurements that are available in the slow loop. Wind MPPT multiplies the peak current and voltage to obtain power, compares the result to a previous value, then steps the duty cycle to a different value. If the power has increased, then the duty cycle will be incremented in the same direction as the previous iteration. However, if the power decreased, the duty cycle will be incremented in the opposite direction.

Solar MPPT is performed with a similar algorithm, but the measurements and controlled variable are different. Solar MPPT is based upon the solar portion of the battery current. This way, the voltage remains relatively constant with the battery. It is calculated by subtracting Vienna current from the total battery current. This is shown in the formula below. Solar MPPT is controlled by allowing the bus voltage to fluctuate. The bus voltage is controlled by the output buck converter. Because it is connected to a reasonably stable output, a battery, its duty cycle directly affects the bus voltage.

$$I_{solarbatt} = I_{batttotal} - \frac{I_{Vienna}}{D_{buck}}$$

Battery charging is important to the health of the battery. Output current and voltage limits are implemented to directly limit the output buck converter and indirectly limit the Vienna rectifier. Battery voltage limit is set to 14.4V. At this voltage, the output current should be zero. The output current begins to ramp down at 14V. Alternatively, this energy maximizer could be used to charge a 24V battery bank, in which case the ramp voltage is 28V and the off voltage is 28.8V. The output current limit depends on the battery bank size, and what the load current is. A sophisticated dv/dt algorithm could be implemented in the battery charging controller to limit the change in voltage over time. This would enable safe charging of the battery bank and it would allow high current loads to draw as much as they need. It restricts rapidly rising battery voltage be reducing current. This would prevent a 'fast charge' from damaging the lead acid battery bank. Additionally, monitoring dv/dt would allow the current limit to be automatically set without any input regarding battery capacity. However, implementing such a system was not necessary or pertinent to this HPS thesis.

6.2.4   Slow Loop Controls, Alternating MPPT

This section describes the slower MPPT method that relies only upon battery current. Just like the other method, control algorithms in the slow loop are allowed to run every 45 milliseconds and include solar MPPT, wind MPPT, and battery charging. The two MPPT algorithms take turns running until they converge upon a maximum power point. For example, the wind algorithm will run at 1.5Hz, changing the Vienna duty cycle to maximize battery current. Then,

once the current has been maximized or a certain number of steps have been taken, the solar algorithm will run at 3Hz, changing the bus voltage to maximize battery current. In this method, each algorithm influences the other, but ideally it will still find the two maximum power points eventually. Rapidly changing sources could affect this algorithm more than the simultaneous one.

6.3 HPS Prototype Summary

The HPS prototype converter created for this thesis involves sophisticated hardware and software. These different aspects are each composed of subsystems that can be independently developed and tested. Solar and wind components can be individually tested once the control systems and safe limits are implemented in software. The combination of these aspects can be tested against the hypothesis and improve upon the state of the art in Hybrid Power Systems.

7   TESTING AND EVALUATION

This chapter describes the testing procedure and the hardware required for testing. Additionally, it describes the results obtained from three different test programs. The first program alternates between wind and solar MPPT to find each independent maximum power point. The second introduces a compensation that reduces the influence that a changing bus voltage has upon the wind maximum power point. The third and final program performs MPPT simultaneously for each source.

7.1   Test Setup

A test bench had to be created to test the HPS. It used parts from the original wind converter test bench, and added some new ones to allow solar and hybrid testing. The original wind test bench employed a Solar Array Simulator (SAS) to drive a DC motor. The DC motor transmitted power to a three-phase wind generator through a chain. This is shown in Figure 7-1. The three phases from the wind generator are then connected to the power converter. This setup allows variable loading of the wind generator to change the loading on the DC motor, which would cause movement along an IV curve defined in the SAS.

Figure 7-1: Wind generator (left) and DC motor (right) in HPS test bench

To add solar capability to this test bench, an additional SAS was incorporated. Both SAS were

controlled by the Solar Array Simulator Interface created by ApECOR. This computer program
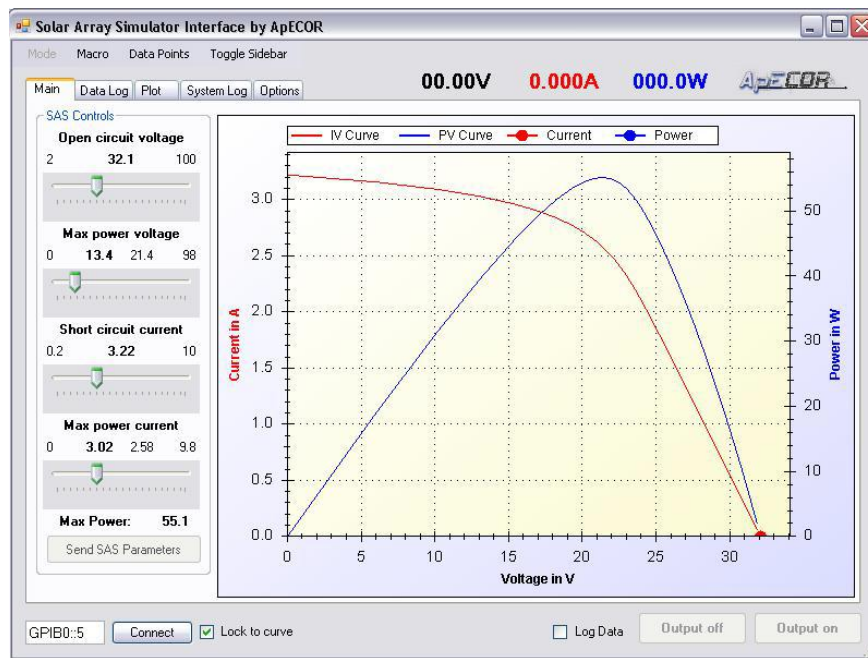
allows control of the IV curve parameters.

Figure 7-2: Solar Array Simulator Interface

7.2   Alternating MPPT HPS

The test for alternating MPPT involved providing the converter with a constant simulated wind intensity and solar intensity. The tracking time was then measured to produce a quantifiable measure of the algorithm's performance. However, this measure is not absolute. Slightly different wind and solar conditions could produce different results, and rapidly changing conditions could produce even more diverse results. Despite these possibilities, this measure has been deemed adequate for comparing algorithms on the same hardware with identical environmental conditions.

Figure 7-3 shows the voltage of the two solar array simulators. The yellow one, which was powering the wind turbine, converges to a steady-state value after 25 seconds. The pink one, which was connected to the DC bus, converges to a steady-state value after 15 seconds.
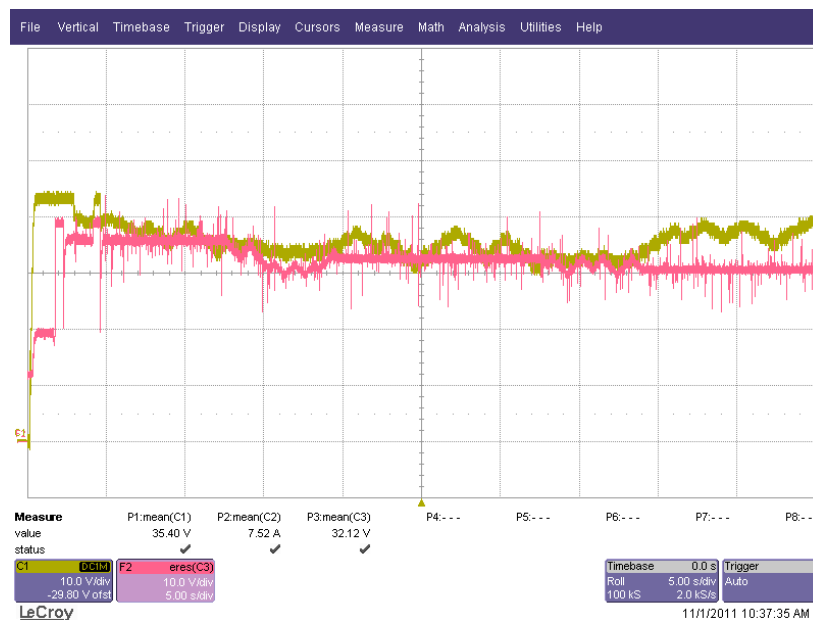

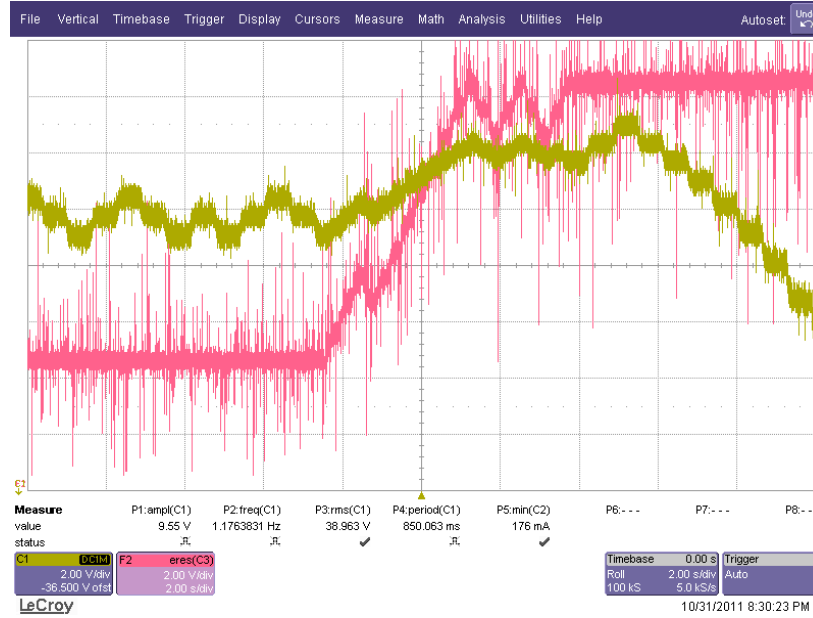*Figure 7-3: Waveform capture showing converter startup*

Figure 7-4: Waveform capture showing solar influence wind

Figure 7-4 shows a weakness of this MPPT method. Though the MPPT algorithm alternates between solar and wind, the wind was in fact influenced by the solar power point. As the pink bus voltage changes, so does the yellow power point of the wind turbine. This is explained by the transfer function of the Vienna rectifier. This transfer function of a boost converter, shown below, is identical to the transfer function of a Vienna rectifier, when in the positive half-cycle.

$$V_{in} = V_o D$$

This function describes the relationship between the input turbine voltage, the output bus voltage, and the wind duty cycle. If the duty cycle remains constant but the output voltage changes, the input voltage must also change. This is the case when wind MPPT is stable, but solar MPPT changes the bus voltage. It causes the wind voltage to change, therefore changing the wind power point.

7.3 Alternating MPPT HPS with compensated duty cycle

In this test, the wind duty cycle was compensated when the bus voltage changes. This was in response to the wind power point changing as the solar power point was adjusted. Figure 7-5 shows a more stable wind power point than in Figure 7-4. This algorithm offsets the change in solar voltage by compensating the wind duty cycle. When the pink bus voltage began to change, the yellow wind voltage remained much more stable than in the uncompensated example.

This compensation consists of adding a constant to the wind duty cycle to account for a changing bus voltage. It is more immune to sensing noise because it does not rely upon any measured values, only upon the desired values.
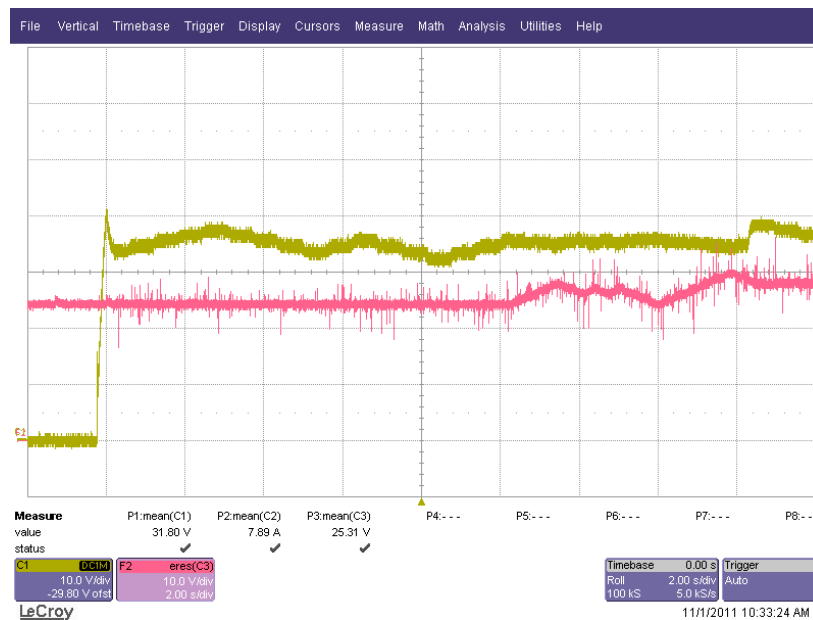

Figure 7-5: Waveform showing wind less affected by solar voltage

7.4   Simultaneous MPPT HPS

Difficulty was encountered when implementing the simulated simultaneous MPPT algorithm. Due to hardware limitations, no running results were obtained. One hardware limitation encountered was inaccurate current sensing on the Vienna stages. The sensing IC has output drift when the bus voltage changes. This was not a problem, and as such, wasn't noticed in the original purpose for this charger. Under solely wind power with a constant bus voltage, the measured current experiences no drift. Figure 7-6 shows the bus voltage in black, and current sense value in teal. In this test, there was no current passing through the Vienna converter, but the current sensor reported a large spike that took 200 seconds to recover from.
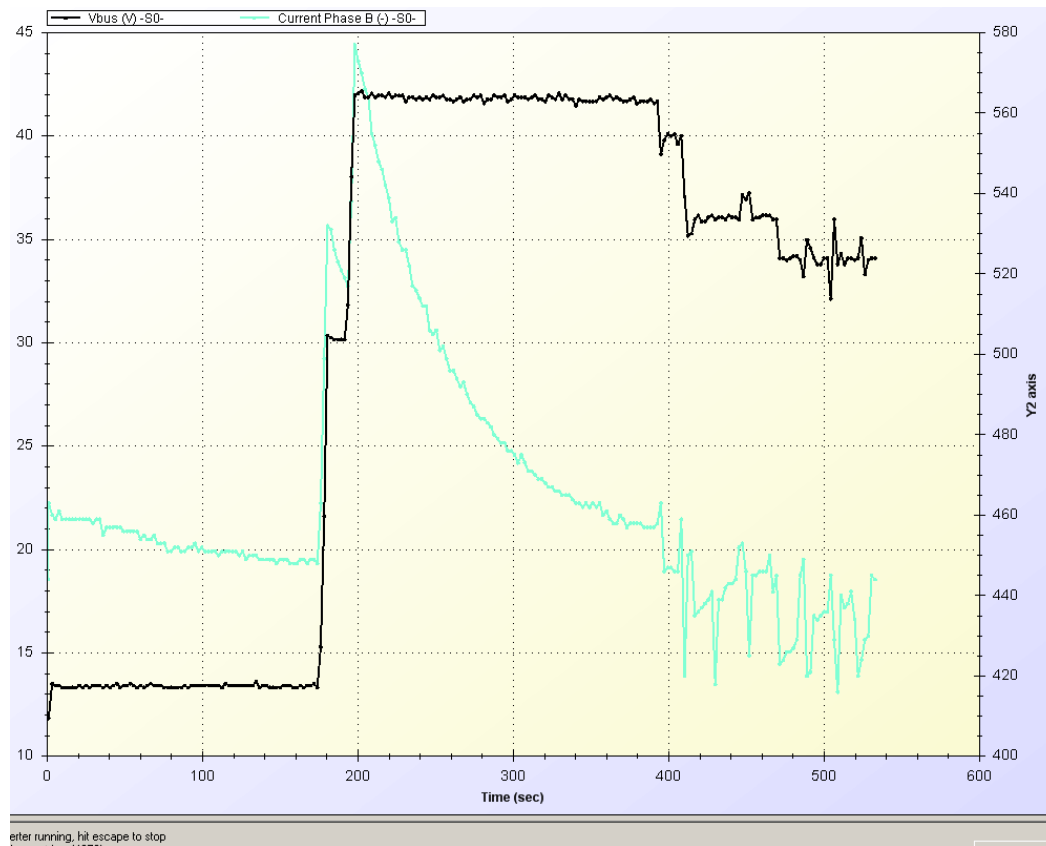
Figure 7-6: Vienna current sensing problem

8   CONCLUSION

This thesis described the research, design, simulation, and testing of a Hybrid Power System. This particular system began as just a wind energy maximizer, but was converted into a wind and solar HPS. This proved the hypothesis correct, because a series-architecture HPS was designed, built, and tested. This HPS employed fewer power stages than typical systems to reduce loss and cost. In addition, the number of current sensing circuits was reduced to also reduce cost.

The MPPT algorithms simulated and tested in this thesis have been proven to be viable as an HPS control system. First, alternating MPPT was simulated. This performed well, but had difficulty with rapidly changing sources. Compensation was developed to reduce the effects of the solar panel on the wind turbine. After simulating the alternating MPPT a simultaneous method was developed and simulated. The simultaneous method involves subtracting the measured wind power from the measured battery power to obtain a measure of solar power. This worked well in simulations and could be used on an upgraded version of this hardware.

In physical testing, the alternating algorithm worked as expected. The compensation improved MPPT ability, but it performed well without it. However, the simultaneous algorithm did not perform as expected. Current measurements proved to be too irregular and inconsistent to obtain usable results.

This research should be continued to increase power output and decrease cost for HPS. Some specific continuations include redesigning the hardware for more reliable current sensing, increasing the power output and energy density, and continue working on simultaneous MPPT.

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