Integrated Renewable Power System (IRPS)

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ABSTRACT — **This paper presents the design and methodology used to create an integrated renewable power system that uses wind and solar energy to charge the battery at the same time in order to optimize energy efficiency of both source. In response to the growing demand for renewable energy sources, how to increase wind and solar energy efficiency is becoming more and more important. However, in theory, it is difficult to use both source to charge the battery at the same time. A microcontroller-based controller is designed to control the charging system. It will detect the instantaneous variations of both wind and solar source, and then optimize the charging operation through proper charge controllers. The microcontroller-based controller presented in this paper is able to not only optimize the efficiency of the system but also improves the stability from relying on one source solely. A 300W wind generator and 60W solar cell panel are used to substantiate the practicability of this integrated operating system.**

Index Terms — **energy efficiency, integrated operating, wind turbine, solar energy, batteries, field test, inverter**

I. Introduction

As the demand of energy increases, renewable energy has become more and more popular among all of the energy forms. However, since the nature of natural resources, such as solar and wind, are unstable and uncontrollable, the performance of a solar or wind system independently can be quite inconsistent. Moreover, relying on solar or wind source solely may not be able to produce enough power to satisfy the power consumption. Therefore, it becomes appealing more than ever to create a power system including the following characteristics: environmental friendly, energy and cost efficient. In general, wind and solar are integrated together in a power system synergistically to improve the overall stability. Nevertheless, in reality, it is difficult to charge the battery using both wind and solar energy at the same time. This is because the voltage drop across the source impedance of the wind generator and the solar cell are very different. The goal of the project is create an integrated wind and solar power system that optimizes the efficiency and performance of the overall system. The intent is to implement an extremely efficient charge method that will be able to charge the battery bank during varying atmospheric conditions.

II. System Overview

The major components that are required in the demonstration of the off-the-grid integrated wind and solar power system are divided into four categories. The first category is energy source, which include wind turbine and solar panel. The next is control unit containing DC/DC converters, microcontroller based efficiency optimizer, and diversion charge controller. Then, energy will be stored in the battery bank or diverted to the diversion load with respect to the battery charging conditions. The last category is power outlet which consists of a DC/AC inverter and transformer. Users will be able to access the stored energy to run electrical devices. Figure 1 is the overall block diagram of the system. In the figure, the black solid arrows indicate the power flow of battery charge and power output, and the brown dash arrows show the flow of load diversion.

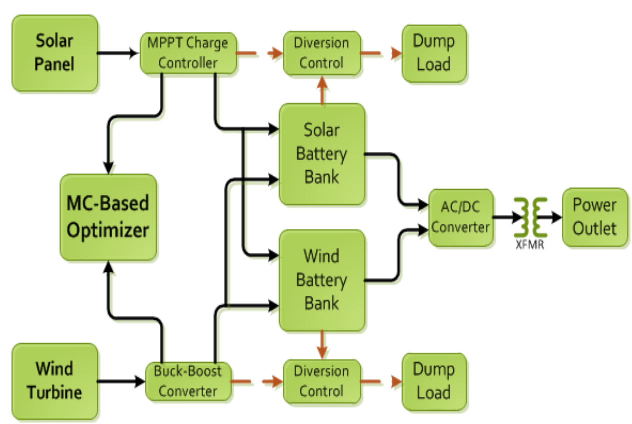


Figure 1 Overall Block Diagram

In order to implement the efficiency optimization of the system, voltage sensors will be inserted in the MC-based optimizer unit. Data from the voltage sensors will be fed into a microcontroller. Then a switching algorithm which adjusts the charging duty cycle ratio of two energy sources to obtain a maximum input to battery bank. Then microcontroller will make switch decisions based on the data it received from the voltage sensors. Battery will be charged in varying atmospheric conditions. Diversion controllers are connected between the power generators and battery bank to monitor the voltage level and divert the exceeding power to dump load to protect the battery.

All of the components for the control unit will be connected in a control box. An LCD screen will be attached to the control box for the users to view the status of the system. In addition, live data is pulled from control box to a computer where a rich user friendly application displays several metrics, status, and quantitative reports. Input voltages from both of the sources, charging mode, temperature, and battery level will be displayed.

III. Power Generation

A. Wind Turbine

The idea of this project would work for a integrated system of wind and solar energy delivers up 1.5 kW for a typical household. For testing and illustration purposes, a wind turbine delivering from 250 to 400 Watts fits this project. The Hyancinth P-300W wind generator meets our needs for the project. It starts producing energy at 3 m/s. According to the vendor, Hyancinth P-300W Wind generator features the specification as the table below.

TABLE I
Hyancinth P-300W Specifications

Specifications	Values
Rated Power	300W
Rated DC Voltage	12/24V
Rated Current	25/12.5A
Rated Speed	900rpm
Max Power	350W
Cut-in Speed	3m/s
Cut-out Speed	15m/s

B. Solar Panel

SunWize builds a solar panel that best suites the needs of this project. SunWize models are designed for warm climate locations and the SW-S85P model is the model that has been selected for this system. This model is within our budget and it has close to the 100W output that was originally desired. The SW-S85P has an open circuit voltage of 22.0V and has been factory configured for 12V use. Since the panel has a short circuit current of 5.4 A, much consideration has been given to acquiring parts that are rated for high current. The Voltage-Current characteristics are presented in Figure 2.

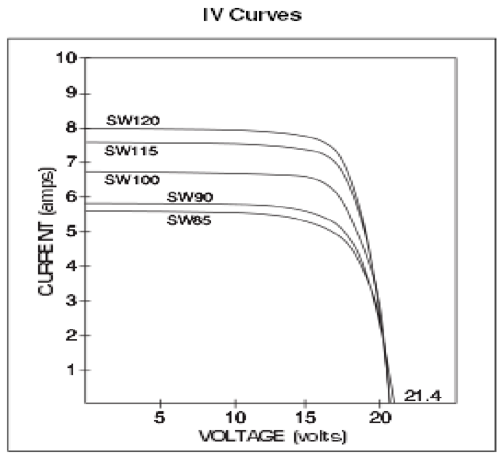


Figure 2 IV Curve of SW-S85P

IV. Control Unit

The control unit contains solar charge controller, Buck-Boost converter, efficiency optimizer, and diversion charge controller. This unit controls and monitors the battery charging process over the system.

A. Solar Charge Controller

This project is more focused on the efficiency of charging the batteries and controlling which source charges which battery. With this in mind and the groups focus more on the control box and the wind turbine control circuit, it was decided to buy a premade charge controller using MPPT. The model that was decided upon was the Morningstar SS-MPPT-15L. This model was selected mainly because it utilizes an MPPT algorithm to maximize the solar energy being collected allowing the group to concentrate on the control aspects of the power flow. The charge controller has a peak efficiency of 97% and only consumes 35mA from the solar panel. This model was also the lowest cost solar charger built for 12V battery charging on the market.

B. Wind Buck-Boost Converter

Since batteries require a specific charging method with different voltage and current levels for each specific stage, output voltage regulation is important for battery charging. Therefore, voltage regulation is needed to extend battery life and optimize the performance.

The voltage output from the wind turbine varies with the wind speed and the rotation speed of the turbine. The voltage of the battery, on the other hand, differs on the load connecting to it. It is essential to have the rectified DC voltage and current match the corresponding battery charging stage at the specific moment to maintain the optimal battery charging.

As a result, a DC-to-DC voltage regulator is needed to increase or decrease the output voltage from the wind turbine to match the charging voltage of the battery. This is also known as switching converters, which tends to have a much higher efficiency than linear converters. Components including power MOSFETs, capacitors diodes and most importantly an inductor are used to transfer power from the source, the wind turbine, to output to the battery. For different purposes of use, arrangement of components varies with different DC-to-DC regulators.

Buck-Boost converters have become more popular in implementing maximum power point tracking applications for both solar and wind systems. In buck mode the voltage decreases as the current increases, and boost mode the voltage is increased as the current decreases. This way the power level will remain the same as it passes through the regulator. For this project, since the wind turbine has the capability to output higher voltage than the charging voltage, a Buck-Boost will be implemented. Therefore, the regulator can boost up the input voltage to match the corresponding charging voltage or buck down the input voltage to a lower output voltage. The challenge is that buck-boost power converters are not as efficient as buck regulators.

After research, LM25118 wide voltage range Buck-Boost switching regulator controller from Texas instruments will be used in this project to regulate the output voltage of wind turbine to the battery. It contains all the functions necessary to implement a high performance cost efficient Buck-Boost regulator by using minimum external components. When the input voltage is sufficiently greater than the regulated output voltage, the LM25188 operates as a buck regulator. As the input voltage approaches to the output, it gradually transitions to the buck-boost mode. This approach maintains regulation over a wide range of input voltages, while optimizing conversion efficiency in normal buck mode.

Figure 3 shows the operation of LM25118 in Buck mode. In buck mode, transistor Q1 is active and Q2 is disabled. The inductor current ramps in proportion to the voltage difference, Vin – Vout, when Q1 is active and ramps down through the re-circulating diode D1 when Q1 is off. For the first order buck mode, the transfer function is shown in equation 1, where D is the duty cycle of the buck switch, Q1 [2].

$$Vout/Vin = D \quad (1)$$

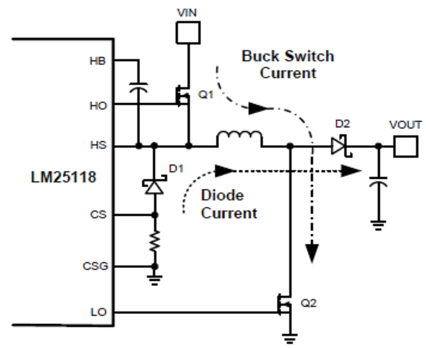


Figure 3 Buck Mode Operation

Figure 4 shows the operation of buck-boost mode. In buck-boost mode, in each cycle, both Q1 and Q2 are active for the same time interval. The inductor current ramps up with proportional to input voltage when Q1 and Q2 are both active and ramps down through the re-circulating diode during the off time. The first order buck-boost transfer function is shown in equation 2, where D is the duty cycle of Q1 and Q2.

$$Vout/Vin = D/(1-D) \quad (2)$$

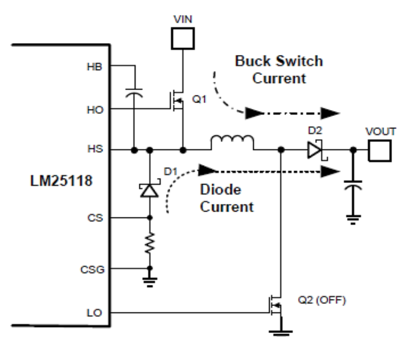


Figure 4 Buck-Boost Mode Operation

The inductor value is determined with respect to the operating frequency, load current, ripple current and the input and output voltage. In order to keep the circuit in continuous conduction mode (CCM), the maximum ripple current should not exceed twice the minimum load current. Moreover, the minimum value of the inductor must be calculated for both buck configuration in equation 3 and buck-boost configuration in equation 4. Compromise has to be made between the two modes.

$$L = Vout\ (Vin1-Vout)/(Vin1*f*Irriple) \quad (3)$$

$$L = Vout\ *Vin2/((Vout+Vin2)*f*Irriple) \quad (4)$$

The resulting inductor values are 20.81 µH for Buck mode and 10.33 µH for Buck-Boost mode. A 14 µH inductor was selected which is resulting from a compromise between those two values.

Since the regulator supply voltage has large source impedance at the switching frequency, input capacitors will be used to limit the ripple voltage at the voltage input. Output filter capacitors are also necessary to smooth out the current pulse from the inductor. Fault protection features are also featured with LM21158 controller, including current limiting, thermal shutdown and remote shut down. An under-voltage lockout input allows the regulator shutdown when the input voltage is below a preset threshold, and the regulator will be put in a very low current shut down state [2].

C. Efficiency Optimizer

Integrate two different renewable energy sources in one solution would be always challenging at the time of designing the platform due to incomparable sources impedances, in this case wind turbine and solar panel. In order to implement such feature in this project, study has been conducted to not only integrate both sources but also to maximize the charging system. Research has been conducted through theoretical analysis and field experiment that traditional method couldn't be used to efficiently charge the battery from wind power and solar energy at the same time [1]. To improve the charging efficiency, the microcontroller based optimizer implements a source threshold algorithm based upon varying weather conditions.

C.1 Analyzing Source Threshold Algorithm (Switching Algorithm)

The analyzing source threshold algorithm is the heart of this project. Microcontroller unit will effectively select the path of the power flow to the battery by analyzing both power sources; such algorithm will be implemented with the aid of sensors detecting spontaneous discrepancy and to maximize battery bank charging. Two separate banks of batteries would be implemented, first one named Esolar and the second named Ewind for simplicity. The system would run under two main categories: *independent* and *integrated*.

Integrated mode would be if sensor reports that only one source is available at the moment, then microcontroller would analyze the data and send the proper signal to open corresponding circuit switches to charge both Esolar and Ewind using one energy source.

Independent mode would be if sensors report that both sources are available and wind turbine is working under threshold limit, then microcontroller will send appropriate signal to open corresponding switches allowing bank Esolar being charged with solar panel output and Ewind being charged with wind turbine output.

A third mode, an extension of independent, is the "wind-enhanced" mode which is not falling into a new category but rather improving it. This special case is depicted as heritance from independent mode conditions with the addition of having wind turbine running beyond threshold limit. Furthermore, the intention of this scenario would be solar panel charge Esolar bank and wind turbine output charge Ewind and also Esolar bank; energy sources are maximized and fluctuations in the wind power generating are decreased [1]. The table below resumes scenario situations in all of the charging categories.

TABLE II

MICROCONTROLLER CONTROL CHARGING MODES

Energy Source	E_{wind}	E_{solar}
Solar Energy		
Wind Energy		
Solar and Wind Energy(low wind speed)		
Solar and Wind Energy(high wind speed)		

C.2 Microcontroller

The Atmel AT91SAM7X512 microcontroller would be used in IRPS pre-loaded with the preference of Netduino boot loader. This microcontroller contains the adequate hardware and software for all design goals, providing enough digital and analog pins to handle all sensors, LCD, and battery charging check, meanwhile at the same time being able to control the IRPS circuitry using pulse-width modulation (PWM) outputs.

Six analog pins would be utilized in IRPS. In order to enable I^2C communication in this microcontroller, analog pins 4 and 5 are going to be used. Occupying two analog inputs will reduce the available number of analog inputs to four cause of IRPS will utilize two I^2C components (DS1624 temperature sensors). Four analog voltage sensors take up the leftover four analog input pins. Every I^2C device carries a unique address to allow a precise identification on the bus and up to 127 unique peripherals may be contained on a single I^2C bus. Hence, if any extra device needs to interact with microcontroller, I^2C compatible parts would be highly recommendable over analog devices. In case that only analog device can be further implemented due to certain limitations, then it is deemed necessary to include analog-to-digital converter in order to be in harmony with I^2C bus.

In the microcontroller digital output pins implementation, most of the pins will be assigned to specific functions. First, it is attributed the digital pins 2 and 3 to the LCD since it uses serial transmission; such pins are better described as TX and RX and are part of the UART. Auxiliary, microcontroller will have another UART pins located in digital pins 0 and 1, DTX and DRX, connected to a pc to deploy/debug code. Also, such port will be used to establish a transmission between microcontroller and a pc to obtain live data from IRPS system. Finally, the four PWM output located at pins 5, 6,9,10 will be controlling the circuitry logic focused in the charge controllers to implement the right stage of charging, the addressing of voltage flow to batteries or dump, the threshold energy source charging mechanism, and all others function in the IRPS.

C.3 Sensors

A standard voltage divider will be implemented for the micro-controller to be able to sense the voltage from both batteries as well as the solar panel and wind turbine. This can be seen in Figure 6 below. The micro-controller can input a voltage of 0V to 3.3V on the analog pins. The resistor values are chosen to correctly divide the input voltage into a usable amount for the micro-controller.

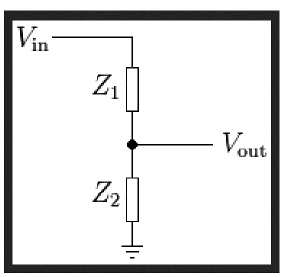


Figure 6 Voltage Divider Circuit

The micro-controller cannot receive a voltage signal higher than 5V or it could be damaged. The solar panel is capable of creating a 22V output which is higher than the wind turbine; therefore equation 5 will be used to calculate the resistor values.

$$V2 = \frac{R1}{R1+R2} Vp \tag{5}$$

The first resistor value R1 will be chosen as 1MΩ, V2 is 5V, and Vp is equal to 22V. This will give a starting point value for R2 that will guarantee that the micro-controller will not input a voltage higher than 5V. After the voltage divider a low pass filter will be on the output of the sensor to help clean up any noise that might be passing through the circuit.

To approximate the current going to the battery, voltage sensor will be placed between the sources and the batteries. In the case of this project, one voltage sensor at the solar MPPT, one at the wind turbine, and one at each battery will be implemented. By modifying the shunt resistor method, the voltage drop between the source and the battery will be the voltage loss due to the resistance of the wires. By applying Ohm’s Law, the resistance of the wires will be obtained by measuring the current going from the source to the battery. Therefore, instead of using current sensors, the group is able to acquire the current to determine the charging stages of the batteries.

C.4 Switching Circuit

The switching circuit is connected directly to the analog outputs of the microcontroller on the PCB. This circuit allows the system to enter a “share” mode for either the solar or wind DC sources. As discussed early the switching algorithm is broken down into four modes. Three of the four modes calls for either the solar panel or the wind turbine to share its voltage to the other sources battery. The schematic can be seen in the Figure 7 below.

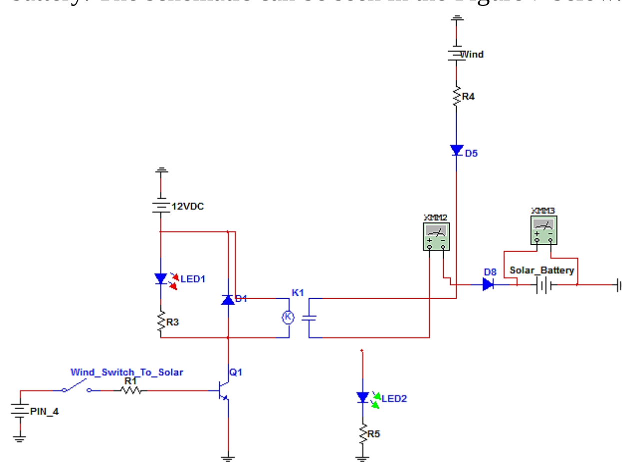


Figure 7: Switching Circuit Schematic

Diode D5 in will have 12V from the battery or the solar panel depending on which is available. When the system needs one of the two power sources to share its voltage to both batteries, the micro-controller will send 3.3V from the analog outputs. When transistor Q1 receives this voltage it will turn on and allow the 12V in the diode to pass to the relay which will then switch and voltage will pass to both batteries.

D. Diversion Charge Controller

The main reason a system needs a diversion charge controller is to protect the battery bank from overcharge and over discharge. The charge controller circuit design is based on a 555 timer IC chip. The circuit is shown in the figure below. The circuit needs to be calibrated for a charging window. 11.9V and 14.9V are set as the low and high set points for the controller. These are the points where it switches from sending power to the batteries to dumping power into a dump load, and vice versa. The diversion charge controller will monitor the battery voltage. When the voltage level rises to a pre-determined level, a sufficient sized diversion load will be connected to the energy source to prevent the battery voltage from increasing any further. The implementation of the diversion charge controller effectively protects the battery from over charging.

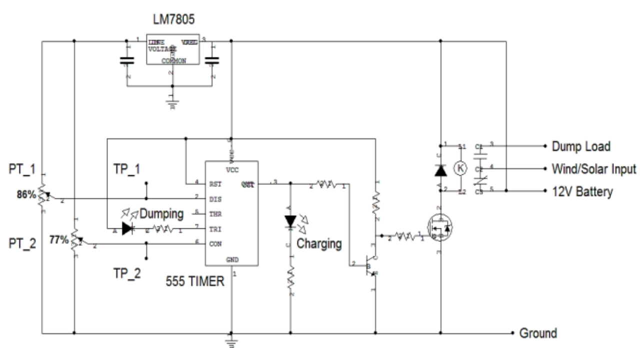


Figure 8: Diversion Charge Controller Schematic Circuit

V. Energy Storage and Diversion Load

Battery is the most popular and technologically matured energy storage option. It is very important to adapt batteries within the stand-alone renewable power system, especially hybrid solar and wind power generation system. The battery bank improves the overall efficiency and consistency of the system by ensuring that there is sufficient supply for the load. It also balances the energy within the power system.

Meanwhile, the dump or diversion loads are design to deal with the exceed power that are generated from the solar panel and the wind turbine.

A. Battery Bank

Energy storage must be optimized to ensure the most effective sizing of each of the system components. When choosing a battery type for the integrated renewable energy applications, there are many factors must be taken into account. Those important comparison criteria are possible depth of discharge of the battery, cost, number of charge or discharge cycles the battery can tolerate, efficiency and technology maturity. Many different types of batteries were researched for the system including lead-acid and lithium- ion. As a result, deep cycle lead-acid battery is considered the most cost effective and favorable for the renewable power applications. Among the types of lead-acid batteries, AGM battery was selected for energy storage in this project. This type of batteries possesses all of the advantages of the gelled electrolyte batteries, but they are much durable. Most importantly, there is no need to adjust the charging voltage due to the extremely low internal resistance. There will be almost no heating of the battery even under heavy charge and discharge current.

The specific battery chosen for IRPS is the Universal Power Group (UPG) UB12180 D5745 Sealed AGM-type Lead-Acid Battery. The battery is rated for nominal 12 volts and 18Ah capacity at a 20 hour (0.90A) charge rate. Moreover, the battery also features small self-discharge of 3 to 6 percent per month, and no need for additional water. It is efficient and reliable energy storage for this project.

The charging algorithm used for this type of battery specified by the Universal Power Group is similar to the standard lead-acid charging algorithm. Three stages will be included. The bulk charging stage will use up approximately half of the charge time, and charge up to 70 percent of the capacity. When the voltage of the battery reaches the predetermined voltage level, which is set to be between 14.5 to 14.9 volts varying with the temperature, the second stage, topping stage begins. During this stage, the remaining 30 percent of the battery will be charged. When the current of the battery has dropped to 0.3 ampere, the battery is considered fully charged. Then the third charging stage, floating charge, begins. The purpose of this stage is to offset the loss due to self-discharge.

B. Diversion Load

Ohm’s Law will be applied to the calculation of diversion load. The diversion load system needs to be able to dissipate the maximum power of the wind turbine and solar panels used in the project to protect the generator and the batteries. The maximum power that will be dumped by the diversion load is 350 watts and 70 watts. WindyNation12-volt dump load resistors will be used in this project. The resistors have an internal resistance rating of 0.73 ohms. The amount of power the resistor will consume can be calculated by manipulating Ohm’s Law equation. Hence, 268 watts power will flow through one of the load resistors.

To use this dump load resistor to dissipate 350 watts of power, multiple 268 watt resistors can be wired in parallel. The wattage of the dump load becomes the sum of each load. Therefore, two of those resistors are needed to be wired in parallel. Since it is necessary to choose dump load that exceeds the maximum output of the complete system by at least 20 percent to protect the generator and battery from potential destruction, two parallel connected resistors and one single resistor are sufficient for the wind and the solar.

VI. SOFTWARE

Software residing inside microcontroller will have one main method named IRPSFullScale(), which is divided in important concepts to be implemented:

```
CheckSolarBankSensor();
CheckWindBankSensor();
SetCurrentStorageStatus();
CheckWindTurbine();
CheckSolarPanel();
ThresholdAnalysis();
ChargingProcedure();
CheckTemperatureSensor();
PrintSystemStatus();
TransmitMicroReadings();
```

These functions will read every sensor connected to both sources and battery banks. They will be responsible for setting the system to current storage configuration based on whether banks are available or not. Also, they will analyze what is the more efficient mode of charging based on current conditions and will interact with circuitry to set the resultant mode. Finally, functions will wrap collected data and print it to the LCD screen at the same time that a new safe thread is created in the code to transmit all of the data to the computer, respectively. This technique is used to avoid possible serial communication exceptions that could affect the main algorithm. This project is targeting the efficiency that can be achieved through the optimal decision over renewable sources available to maximize power delivered.

VII. USER INTERFACE

IRPS is built with a monitoring user friendly application, granting a live status condition of control box system. Application possesses a background thread always listening to controller box data to be sent through a serial USB-TTL cable. The intention of IRPS with such application is to take the data collected to a different level of usefulness for the final user. Data is being transmitted wirelessly to the PC at a baud rate of 9600 bits per second and it is continuously time stamped and saved to selected storage engine.

Application was developed in Windows Presentation foundation platform (WPF) using Microsoft Visual Studio as IDE and CSharp as language. Both microcontroller and user application were programmed using same language and IDE bringing a completely integration when comes to data codification, synchronization, and communication strength. Application is powered by SQL Server Compact database which is widely used in the industry and allow this user interface not only being informative but also having an excellent performance when running analytics reports. Figure 9 shows a view of main screen where it can be observed live data monitor, system current status, current weather, three analytical reports and system settings configuration.

Figure 9 IRPS User interface

VIII. PRINTED CIRCUIT BOARD DESIGN

Custom printed circuit board has been designed using CadSoft's Eagle PCB Design software. The final design is 9.90 x 5.90 and was manufactured by Advanced Circuits. The largest trace widths are 0.056 with 2 ounces of copper in for a 5A capability at a rise temperature of 15°C. The bottom layer of the two-layer board will be a ground plain which will help to reduce external noise to the electronics and keep all grounds associated. A similar technique was used for the 5 V and 3.3 V voltage regulators in order to obtain the best efficiency.

IX. TESTING

A testing plan was created to ensure that all the features and parts of IRPS works as desired. Each part was prototyped using breadboard and some of them in soldered vector board. Individual components were tested using Netduino development board to ensure accuracy. Power components were tested individually and replicated before integrating them with rest of circuitry. PV panel and wind turbine were monitored outdoor while attached to couple of voltmeters to obtain outputted voltage and current. Batteries were safely discharge and charge using one and two sources. System level testing will take place when all components are connected together. System will target important goals such as correct charging mode, appropriate efficiency and performance of power delivering, LCD and sensors operational, battery banks are being charged/discharged, inverter supplying power, and accurate data being transmitted from microcontroller to computer to be saved into application database. User interface is expected to show current system status as well as to run a variety of reports over collected information.

X. Conclusion

Ultimately the solar panel is mounted onto a custom designed iron frame with wooden board on the bottom for stability. The wind turbine is mounted to the same base with the solar panel. All of the designed boards, including Buck-boost converter, sensing circuit, efficiency optimizer and diversion charge controller, are screwed inside a rectangular box. The system can be easily transferred to different outdoor locations. These design features were included to help make the IRPS module appealing to alternative energy researchers. The most important point is the efficiency of the system, and is addressed through the use of efficient components, and the implementation of switching charge algorithm. This algorithm allows the system to be as efficient as possible through constantly changing atmospheric conditions.

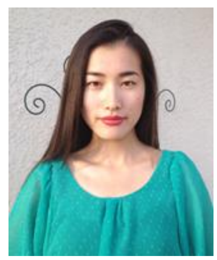
Acknowledgement

The authors wish to acknowledge the financial support from Progress Energy and Dr. Richie for facilitating this grant money to fund the project. This project is designed based upon M. Chen’ IEEE conference paper “The Integrated Operation of Renewable Power System.” Also the authors would like to acknowledge Nathan Bodnar from the ARC at UCF for all his help with troubleshooting the PCB design.

Biographies

David Wade is a graduating senior in Electrical Engineering. His hobbies include playing music and traveling. He will be spending this summer playing bass on the Vans Warped Tour and plans on finding employment in the Semiconductor industry afterwards.

Julio F. Lara is a graduating senior in Electrical Engineering. He is a senior Co-Op at Siemens Energy and currently has an offer to work for Siemens Industry as Electrical Systems Engineer. His main areas of interest are in power systems, drive technology and electrical systems.



Jing Zou is a senior in Electrical Engineering with an interest in power system and power electronics. She is currently working as an electrical engineering intern in Power Grid Engineering. Jing will be working as an application engineer for Texas Instruments in Dallas, TX upon graduation.

Karel Castex is a graduating senior in Computer Engineering. He is a senior software architect/developer in .NET framework. His interests include software engineering and lead developing. He currently holds a position as Software Engineer III at Golf Channel, NBCUniversal.

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