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To: Marty Irvin at Center for Coal Technology Research

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Subject: Final Report, Green Cell Phone Towers (A302-10-PSC-CTR-003)

1. Introduction

1.1 Purpose

This report documents the final advancements and accomplishments made in the green cell phone tower project including all activities from the first report in March 2010 until July 28, 2010. This report focuses on the sizing of the components, the battery management system design and implementation, and the test results for the wind turbine emulator, the battery, and the power electronic circuits.

1.2 Project background

In modern cell phone towers, where the tower is located in mostly remote areas, connecting the electric load of the tower to the grid is often costly. In addition, to provide a backup source for the electric grid, a diesel generator, which demands regular fueling and maintenance, is equipped in each tower. Moreover, placing more regulations on environmental protection brings a need for green power sources for every application. An alternative solution for the diesel backup and the grid extension to the location of the cell phone tower is to harvest the renewable energy available at those sites. The height of the cell phone tower brings the advantage of semi-steady wind flows. The increased wind flow introduces the application of wind turbines to cell phone towers. However, since the wind speed statistically varies, in some circumstances, the wind turbines cannot provide the power required by cell phone tower electric consumers. Therefore, there is a need for backup sources to feed the consumers for a specified period of time. Batteries are suitable candidates for these applications, since they can provide high power for long periods of time. A control system to regulate the power flow can manage battery charging according to the net power available from what the wind turbine provides and what the load consumes. The overall approach is to provide methods to design and size an autonomous wind turbine power system for cell phone tower applications.

1.3 Scope of this report

This report provides the status of all tasks described in the accepted white paper and final report on all activities and results obtained. The statement of work in this research includes:

- Modeling and sizing of system components
- Supervisory control system development
- Simulations
- Hardware implementation
- Battery charge control unit design
- Battery charge control unit manufacturing
• Battery charge control unit experimental results
• Battery discharge control unit design
• Battery discharge control unit manufacturing
• Battery discharge control unit experimental results
• Continuous charge and discharge operation of the battery control unit
• Wind emulator and system response

2. Status of tasks

2.1 All tasks have been successfully completed

Background

The ever-increasing public awareness regarding global warming, the accelerated usage of existing non-renewable energy sources, and the Kyoto Protocol have all forced researchers to improve and advance new alternative energy sources that are sustainable and renewable. Wind power is one of the most promising and feasible sources of renewable power. Wind energy, as a renewable energy source, has the potential of being cost effective with a high capacity factor. Currently, most commercially operating wind turbines have horizontal axis designs with variable-speed electric power generation.

Naturally, the blades interact with the wind and convert wind energy into mechanical energy at the shaft. The wind turbine, which includes couplings, dampers, and gear boxes, conveys the mechanical energy harvested at the blade shaft to the shaft of the generator system. The generator system, with its generator and power electronics, performs electro-mechanical energy conversion to generate the electrical power to the power grid. Typical wind turbine characteristics are shown in Figure 1.

![Figure 1, Wind turbine characteristics](image)

Telecommunication towers in urban and rural areas normally receive their electric power from the power grid extended to their locations. A diesel generator feeds part of the tower’s load in emergency conditions. In either case, telecommunication towers make use of the power that is generated from fossil fuel. On the other hand, the unique geometry of these towers, specifically their height, provides an abundant and stable wind speed, which results in wind power harvesting opportunities. Harvesting
this energy and utilizing it for the electric load of the tower could reduce the amount of air pollutants. In addition, if the wind turbine generates the power required for the electrical equipment of the tower, there is no need for grid expansion.

Standalone application of wind turbines has been reported for many applications including water pumps, hydrogen generation plants, compressed air plants, and electric vehicle charging systems. In all of these systems, a supervisory control unit is required to manage the charge in the system; however, the type of load varies from pumps to electric vehicles that are not categorized as very sensitive. Telecommunication towers, on the other hand, are very sensitive regarding power interruptions and frequency fluctuations. In this regard, very precise and fast control techniques and multiple backups are required. The geographic locations of these towers result in various wind profiles. Since wind power cannot completely provide the base load for very sensitive consumers, there is a need for power storage to regulate the output power of the system.

This research investigated the sizing, design, and implementation of a wind power plant for telecommunication towers.

**Theory and Methods Used**

In this research, the application of wind turbines in a local power system of a cell phone tower is studied. The idea is to use wind turbine/generators to provide electric energy for the repeaters and switches in cell phone towers. The power system contains a storage device that provides energy for the load in low-wind events. A power management system is required to supervise the power generated from the wind turbine/generator, the charge/discharge of the storage, and the load regulation.

The main part of this research was the design of an integrated supervisory control system to be implemented in fast prototyping devices such as dSPACE to control the charge and discharge and to measure the power generated from the wind turbine. In this regard, power electronic circuits needed to be designed and manufactured to charge and discharge the battery at a certain rate (voltage and Current). The State Of Charge estimation technique was developed to estimate the real-time SOC of the battery and to enable accurate control over battery management. A supervisory control system was developed to control the charge and discharge rates of the battery by generating PWM signals and to enable/disable signals through fast prototyping devices. Matlab/simulink and dSPACE hardware were used to design and implement the controller in the hardware for system operation demonstration. The typical standalone wind power system components, including the supervisory control system and its overall connection to other parts, are shown in Figure 2.
As Figure 2 shows, a standalone wind battery power system consists of several subsystems including the wind generator, the power converters, the battery unit, and the supervisory control unit. In the following section, the sizing procedure, design, and implementation details of these systems are discussed and their successful experimental results are demonstrated.

**Task 1: Battery Backup Sizing and State Of Charge Measurement**

The energy stored in the backup batteries can be directly used to power DC loads, or it can be inverted to power AC loads. Deep cycle batteries are recommended for renewable energy systems. The proper sizing of the battery bank ensures a sufficient reserve capacity to power the load of the cell phone tower without running additional generators. The battery bank should be sized as a standalone power supply for a specified time. Power system data is required to properly size the battery bank, including:

- Watt-hours of electricity usage per day
- Number of Days of Autonomy
- Depth of Discharge limits
- Ambient temperature of the battery bank

*Electric Power Usage Per Day*

An accurate estimation of the power load in the cell phone tower is required to correctly size the battery bank. The load list of the tower equipment precisely provides this information. The electrical usage should be identified in Watt-hours (Wh). A 4-6kW load is expected in cell phone towers.

*Days of Autonomy*

To properly determine the total electric power required for the entire duration of battery power, the number of days of autonomy must be determined. This parameter illustrates the total energy that a battery must provide if there is no means of charging the battery. Relying on wind turbines, days of autonomy may reach up to 4-5 days. More accurate information can be found at the weather measurement station or at airports of the cell phone tower geographic locations. For solar panel powered systems (PV), the
number of days of autonomy is represented by the number of cloudy days in a row that might occur and for which the system should have stored energy.

For systems with more than 5 days of autonomy, the size of battery backup becomes very large, which may defeat the economic benefits. In this case, backup energy should be provided by additional sources such as a diesel generator, and thus, the days of autonomy are the total number of days the battery backup should be able to provide the load without using the diesel generator.

**Depth of Discharge**

The planned Depth of Discharge (DOD) of the battery bank determines the percentage of battery power that can be used in each discharge cycle. Flooded lead acid batteries (FLA), sealed AGM batteries, and sealed gel batteries are rated in terms of charge cycles. One cycle completely discharges the battery from its fully charged state and then charges it back to its fully charged state. The DOD is the amount of energy (percent of total capacity) that can be taken from the system. Higher DOD values shorten the battery lifetime. Figure 3 shows the battery lifetime as a function of DOD.

![Figure 3, Battery life based on Depth Of Discharge](image)

Battery manufacturers provide a safe operating DOD; however, a general recommendation suggests that DOD values should not exceed 50% of the total capacity. For off-grid applications, a 25% DOD will extend the battery life significantly. For applications that use batteries occasionally, as a backup system for example, the DOD can be set to values of 50% or more.

**Temperature**

Battery lifetime and capacity are affected by temperature. The temperature standard for most battery ratings is about 77°F. In colder temperatures, the battery capacity is reduced, while higher temperatures shorten the battery life. Therefore, an indoor location for batteries in colder climates is recommended. In cell phone tower applications, the battery backup unit should be placed inside the powerhouse. FLA batteries cannot withstand freezing temperatures; sealed batteries can operate in sub-freezing temperatures; however, their capacity will be reduced significantly. A de-rating factor should be considered for sizing the batteries in colder climates as shown in Table 1.
<table>
<thead>
<tr>
<th>Temp in Degrees F</th>
<th>Derating Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>80+</td>
<td>1</td>
</tr>
<tr>
<td>70</td>
<td>1.04</td>
</tr>
<tr>
<td>60</td>
<td>1.11</td>
</tr>
<tr>
<td>50</td>
<td>1.19</td>
</tr>
<tr>
<td>40</td>
<td>1.30</td>
</tr>
<tr>
<td>30</td>
<td>1.40</td>
</tr>
<tr>
<td>20</td>
<td>1.59</td>
</tr>
</tbody>
</table>

**Building System Voltage**

A suitable number of battery cells in series and parallel branches must be considered to build the required current and voltage outputs of the battery bank. The typical voltage levels are 12V, 24V, or 48V.

**Amp-hour Capacity Calculation**

To calculate the amp-hour capacity (Ah) required for the battery, the following algorithm is suggested:

- Identify the total daily use in watt hours (Wh)
- Multiple Wh by days of autonomy to get the total power
- Divide the total power by the DOD factor to get the total discharge power
- Multiple the total discharge power by the temperature de-rating factor to get the de-rated power
- The Ah of the battery backup can be obtained by dividing the de-rated power by the system voltage

**Recommendations for Selecting Batteries to Meet the Amp-hour Capacity**

- It is better to keep the number of parallel branches of batteries to three or fewer. In batteries with more parallel branches, the life of the battery is shortened due to unbalanced charging.
- Batteries should be connected in a series to increase the system voltage. For instance, two 12V, 100Ah batteries can be connected in a series to provide a 24V and 100Ah system.
- Batteries should be connected in parallel to increase the Ah of the system. For instance, if two 12V, 100Ah batteries are connected in parallel, the system will provide 12V and 200Ah.
- To meet the system Ah and Voltage, selections of many configurations can be chosen and are limited only by the types of batteries and the budget.

**Building the bank**

The first step to build a proper battery bank is to first meet the required Ah. A battery should be selected that has a capacity close to the required Ah. If such battery does not exist, 1/2 or 1/3 of the total Ah can be selected. Either case would suggest that two or three branches in parallel could provide the total Ah. Once the type of battery is selected based on the capacity, the number of cells in each of the parallel branches should be selected to provide the required voltage. This number can be set by dividing the battery voltage by the candidate cell. The total number of cells can be found by calculating the product of the number of
branches and the number of cells in each branch. Economic studies can determine which configuration is more financially attractive.

**Task 2: State of Charge Measurement**

*Introduction*

Power generated from the wind is not a constant or timely force; therefore, it is necessary to have a system that compensates for this unreliable energy source. The purpose of a battery backup system is to store and regulate the power delivery of the load when the wind speed varies over time. To properly charge and discharge the battery, an exact estimate of the state of charge (SOC) is required for the supervisory control system.

To efficiently charge and discharge the battery pack when needed, an accurate SOC estimator must be employed. State of charge is defined as the available capacity that a battery can provide. This can be described, as seen in (1), as a percentage of the available capacity compared to the rated capacity.

\[
SOC = \frac{\text{Available Capacity (Ahr)}}{\text{Rated Capacity (Ahr)}} \times 100
\]  

(1)

There are many different ways to provide an accurate measurement. The specific gravity method deals with measuring the weight of the active chemicals in the battery; as the battery discharges, the active chemical is consumed and can then be used to define a direct relationship with the SOC. However, there is a lengthy stabilization required for accurate results. The next method is the open circuit voltage method, which involves using the linear relationship between the open circuit voltage and the remaining capacitance to determine the SOC. However, it also requires a long stabilization period and is not able to be used for online measurements. The next method is the current integration method. This involves integrating the amount of current going into or leaving the battery over a certain amount of time; however, as time increases, the error in the SOC estimation also increases, so this option is accurate for only small periods. The last method models the internal impedance of the battery and then uses that to calculate the SOC.

*Problem Definition*

An accurate state of charge estimator needs to be implemented for use in a wind power battery backup system. The requirements are that it must constantly calculate the SOC and be practical, affordable, and fast.

*Approach/Solution*

From the problem statement, the main requirement that influenced the solution was the ability to monitor the SOC online. This meant that the current integration method was the best solution because none of the other possibilities had the ability to monitor in real-time.

Previous work in the current integration estimator uses the equation seen in (2) to predict the SOC:

\[
SOC(t) = \frac{Q(t_0) + \int_{t_0}^{t} i(t) dt}{\text{Rated Capacity}} \times 100
\]  

(2)
Where \( Q_0 \) is the initial charge of the battery and \( I \) is current. To simplify this equation, it was assumed that the battery was always fully charged before monitoring. Therefore the equation used for this implementation can be seen in (3).

\[
SOC(t) = 1 - \frac{\int_{t_0}^{t} i dt}{\text{Rated Capacity}} \times 100
\] (3)

Once the equation was developed it was then put into MATLAB SIMULINK for simulations.

**Discussion**

By sticking with a simple method, the state of charge estimator was developed with relative ease and quickness. As can be seen from the simulation comparison, the SOC estimator developed in this work compares very closely with the SOC estimator given in the MATLAB battery element.

However, with the simplicity of this design came some problems. As the current integrator functions over time, the amount of error seen in the SOC increases with this time interval. In addition, there are many different factors that affect a battery’s performance that are not simulated using this method. To combat this, a factor \( \alpha \) can be introduced in (2) to model the dependence of the discharge rate with the current. The new equation can be seen in (4).

\[
SOC(t) = \frac{Q(t_0) + \int_{t_0}^{t} i dt}{\text{Rated Capacity}} \times 100
\] (4)

where \( \alpha \) can be found experimentally as (5),

\[
\alpha (i) = \frac{\text{Rated Capacity}}{\text{Available capacity at current } i}
\] (5)

Because \( \alpha \) needs to be found experimentally, it was not yet feasible to add this to these simulations, but as the project moves further along and more data can be generated, it is a viable option to help increase the accuracy of the system.

**State of Charge Simulation**

To use this MATLAB/Simulink block, a circuit needed to be created to be able to measure the amount of current going to and from the battery at any given time. To do this, a circuit consisting of three parts, a voltage regulator, an amplifier, and a current sensor, was designed. The idea behind this is that the current sensor will measure the given current and give an output voltage that has a linear relationship with the
measured current. The voltage regulator will regulate the power from the bus to 5V and supply both the current sensor and the amplifier with power. The amplifier will then take the voltage output by the current sensor and amplify it to provide for a more accurate measurement of current.

For the current sensor, the SCD10PUN, manufactured by CUI Inc., was selected. This was chosen because of its ability to measure high current and its ease of implementation. It is a simple 6-pin device that uses 5 volts to output a voltage from 0 – 2.5V. It has a low max current consumption of 10mA and has a high-operating temperature range from -10° to 75°C. As explained above, it outputs a voltage linear to the input current. This relationship can be seen in Figure 5. From the graph, we can see that the output current can be calculated using (6).

\[
\text{Output Voltage} = \text{Input Current} \times 0.2 + 0.3
\]

Figure 5, Linear relationship of output voltage vs. input current

For the voltage regulator, the LM7805, manufactured by Fairchild Semiconductor, was selected. This was chosen because of its high range (7V to 20V) of input voltage to a fixed 5V output. In addition, like the current sensor it has a high range of operating temperatures, -40° to 125°C.

For the amplifier, the LM358, manufactured by STMicroelectronics, was selected. This was chosen because an amplification of 2 was needed. This was chosen so that the output voltage would be amplified enough to be compatible with dSPACE, a hardware device that will implement our MATLAB/Simulink model in circuit form. In addition, since the output ranges from 0 to 2.5V and the max current is 5, it makes for a nice relationship if the output voltage is amplified from 0 to 5V.

Finally, once the parts were chosen, the circuit was implemented. A schematic drawing can be seen in Figure 6, where the circuit is completely self-sufficient and all that is needed is power and the current to be measured.
Simulations were conducted to verify the output of the MATLAB/Simulink block. To judge the accuracy of the model, it was compared to the SOC parameter of the battery block SIMULINK. This block diagram can be seen in Figure 7. To do the comparisons, the battery was connected to a constant 50 mA current source. Then the developed SOC estimator monitored the current of the battery while the battery SOC parameter was also being monitored.

The results of the comparison can be seen in Figures 8-11 showing the similarities during a discharging cycle.
The results verified that an SOC estimator was realized using the current counting technique. Next, the hardware circuit was tested to verify its operation as well. As can be seen from Table 2, an experiment was run by applying a known voltage across a known resistance and comparing the theoretical and experimental current values. By comparing percent errors, it is clear that the circuit does measure the current within an accurate margin of error of 10% percent.

Table 2, Current measurement values, and current

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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6 V</td>
<td>6 Ω</td>
<td>0.519 V</td>
<td>1.095 A</td>
<td>1 A</td>
<td>9.5%</td>
</tr>
<tr>
<td>9 V</td>
<td>6 Ω</td>
<td>0.622 V</td>
<td>1.610 A</td>
<td>1.5 A</td>
<td>7.3%</td>
</tr>
<tr>
<td>12 V</td>
<td>6 Ω</td>
<td>0.672 V</td>
<td>1.860 A</td>
<td>2 A</td>
<td>7.0%</td>
</tr>
<tr>
<td>15 V</td>
<td>6 Ω</td>
<td>0.817 V</td>
<td>2.585 A</td>
<td>2.5 A</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

**Conclusion**

An SOC estimator was successfully developed and simulated using the current integrator theory. Although an SOC estimator was successfully developed, steps need to be taken to account for the general unpredictable nature of most batteries. Several options are being considered and should be able to be implemented shortly.

**Task 3: Wind turbine modeling and sizing**

The following procedure is recommended for standalone wind turbine sizing that is connected to a storage system:

**Step 1: Site Assessment**

To generate electric power, a minimum amount of wind is necessary. Since cell phone towers are located at high altitudes, the minimum amount of wind is always available. Table 3 provides a good assessment of what the average wind speed can provide in terms of energy generation.
Table 3, Power generation assessment based on average wind speed

<table>
<thead>
<tr>
<th>Average Wind Speed</th>
<th>Wind Regime for power generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 4 m/s ~15km/h</td>
<td>Not Good</td>
</tr>
<tr>
<td>5 m/s ~18 km/h</td>
<td>Poor</td>
</tr>
<tr>
<td>6 m/s ~22 km/h</td>
<td>Moderate</td>
</tr>
<tr>
<td>7 m/s ~ 25 km/h</td>
<td>Good</td>
</tr>
<tr>
<td>8 m/s ~ 29 km/h</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

A general estimate shows that a minimum of 15 km/h wind speed is required to generate economic wind power. A wind map of specific geographic locations shows the possibilities of wind power generation (Figure 12).

![Figure 12, Wind map of the United States](image)

This map shows the windiest regions in the United States. According to the map, most of the coastal areas, the Midwest, and the North central regions are suitable for wind power generation. Regional maps are also available to evaluate the annual information on speed direction and variation of wind. A local weather station, such as the one at the airport, can provide more detailed information about specific areas. In Indiana, the wind maps of four regions were explored for the Green Cell Phone Project (Figure 13).
In addition to the average annual wind speed, more information about site selection is required. Wind turbines should not be obstructed by any object and should be installed in open areas to be fully exposed to the wind. Figures 14 and 15 show how the site should be selected if there is an object on the site. There is more to consider than just the wind when considering a site. For example, the distance of the turbine from where the electricity will be used is also important. The farther the electricity will be transmitted, the more expensive the system will become.

If the wind encounters an object, the speed and power of the wind decrease significantly. The ratios of speed decrease, turbulence increase, and wind power decrease as factors of the object distance are shown in Figure 15. As the figure illustrates, it takes about 20 times the height of the object for the wind to recapture its power again.
Wind speed is required to determine the size of the turbine and the size of the battery storage.

**Step 2: Annual energy and peak power consumption estimation**

In order to size the turbine, the total amount of energy required in a year needs to be determined. The peak power can help determine the sizing of the battery bank.

*Estimating Annual Electrical Energy Requirements*

To estimate the annual energy requirements, the amount of power drawn and the duration for each load should be determined. The power is measured in watts, and the amount of energy is expressed in Wh or kWh.

*Estimating Peak Power Requirements*

To properly size the wind energy system, the maximum amount of power that the system should provide needs to be determined. This amount can be obtained by adding all possible loads that could be on at the same time. The wind power system should be able to generate enough power to feed all the loads.

**Step 3: Size a Wind Turbine and Tower**

One of the main characteristics of wind turbine generators is the amount of annual energy generated at the average wind speed of the geographic location. Knowing the amount of energy required annually and the amount of harvestable energy at each location and altitude can determine the size of the wind turbine. The height of the tower becomes a very important factor in selecting the size of the turbine. In high towers, the wind speed is higher, which results in higher energy generation. Thus, a smaller wind turbine can generate more energy annually. However, at a lower height, the wind speed is lower and causes lower energy generation. To generate enough energy, a larger generator should be used. In addition to the load, a wind turbine should be able to charge the batteries.

*Estimation of Potential Wind Power:*

The power available in the wind is related to the cube of the wind speed.

\[
P = \frac{1}{2} \rho A U^3
\]

where \( \rho \) is air density, \( A \) is area, and \( U \) is wind velocity.

The wind turbine power output depends on wind speed, so it is important to gather and analyze wind speed information of a preferred site. There are four approaches to summarize wind speed information from a given site:

1. Direct use of the data averaged over a short time interval
2. The method of bins
3. Development of power and distribution curves from the data
4. Statistical analysis using summary measures
In practice, the power available from a wind turbine, \( P_w \), can be shown by a machine power curve. Power curves are frequently presented by turbine manufacturers in their marketing literature. The power curve establishes a relationship between wind speed and power output.

Prediction of a wind turbine’s power curve involves consideration of the rotor, the gearbox, the generator, and the control system. The power curve can be predicted by matching the power output from the rotor as a function of wind speed and rotational speed to the power produced by the generator and as a function of rotational speed. Rotor power, \( P \), is given by

\[
P_{\text{rotor}} = C_p \frac{1}{2} \rho \pi R^2 U^2
\]

where \( R \) = rotor radius, and \( U \) = wind speed.

The power coefficient \( C_p \) in the formula is given by

\[
C_p = \frac{\text{Rotor power}}{\text{Power in the wind}}
\]

Wind Turbine Energy Production Estimates:

It’s more useful to estimate how much energy a wind generator will produce at a given site. The power curve is only one factor of annual energy output of a wind turbine. The wind speed at which a turbine generates its peak power occurs only a very small percentage of the time. So the energy output cannot be estimated by only focusing on the peak power output.

Since wind speed is not constant, a specific wind turbine’s annual energy production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. The ratio of actual productivity in a year to this theoretical maximum can be shown as a capacity factor. Typical capacity factors are 20–40%, with values at the upper end of the range in particularly favorable sites.

To determine how often a particular wind speed will occur, a wind “distribution” graph can be used. A wind distribution graph plots the frequency of each wind speed. These curves can be used to estimate the energy yield from a particular wind turbine. It is widely accepted that the Weibull distribution fits the actual wind speed distribution quite well. The Weibull distribution is utilized to describe the principle wind speed variation. Its probability density function is given by

\[
f(v) = \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp \left[ -\left( \frac{v}{c} \right)^k \right]
\]

where

\( v \) is the wind speed (m/s),
\( k \) is the shape parameter, and
\( c \) is the scale parameter (m/s).

Then the average power output can be determined by building a relationship between the power curve function and the wind distribution:

\[
P_{\text{avg}} = \frac{\int_{v_{i-1}}^{v_i} P(v)f(v)dv}{\int_{v_{i-1}}^{v_i} f(v)dv}
\]

where \( v_i \) is the wind speed range.
where \((V_{i-1},V_i)\) is the interval of the highest possible wind speed in a particular site.

The annual energy output can then be calculated by

\[
E = P_{ave} \times 8760 \text{hr/year}
\]

(14)

**Step 4: Balance Of Plant (BOP)**

To balance the plant with the on-demand load, a backup power source is required. In section 2.1, Task 1, the sizing procedure for a battery backup was explained. Since telecommunication systems require a highly reliable source of energy, a hybrid system is required. A hybrid system will provide power from different sources of energy, such as a battery and a diesel generator or a battery, a solar panel, and a diesel generator.

**Task 4: Building a Wind Generator Emulator**

Two universal AC/DC motors were used to provide a variable-speed prime mover and a generator to mimic the wind speed at low and high conditions. A wooden base was built to mount and couple the prime mover and generator. An autotransformer was used to control the voltage at the terminal of the prime mover, and hence control the speed. The field winding of the generator was connected to the same source with a half wave bridge rectifier and large capacitor to smooth the DC output of the rectifier. A rheostat was used to control the amount of current that the field winding was drawing from the source, and hence, to provide a controllable output voltage at the generator terminals. The armature of the generator was connected directly to the load through the control circuitry, and the voltage was controlled by motor speed and field resistance. This unit was also equipped with a digital speed sensor that allowed precise adjustment of the generator speed. Initial load testing was done using a 100-ohm resistor to simulate a load.

![Figure 16](image)

Figure 16, Wind turbine generator along with the excitation, speed control, and speed measurement, designed and built in the IUPUI Engineering Technology Department.
Figure 16 shows the wind turbine and generator emulator. The field excitation and system diagrams are shown in Figure 17.

![Schematic diagram of the motor generator coupling and excitation system](image1)

**Figure 17, Schematic diagram of the motor generator coupling and excitation system**

Several tests were made using an input AC voltage of 10 to 20V. As the voltage was increased, the field current was increased because it was rectified from the input voltage. This also increased the output DC voltage as a function of the speed and field current. These changes were made for different amounts of field resistance to show how that changed the output voltage. As the resistance was lowered, the field current increased and resulted in an increase in the output voltage.

To increase the scope of renewable energy sources in cell phone towers and to increase the reliability of system operation, the battery charge control board was designed to operate with Solar Photovoltaic panels as well as wind turbines. The solar panel used in this research is shown in Figure 18.

![Solar panel](image2)

**Figure 18, Solar panel used as a renewable energy source, shown with light projectors to control the light intensity and power output of the device.**
Task 5: Design and manufacturing the charge and discharge power converters

Power electronic circuits are used to increase or decrease the voltage levels in the output of their circuit to send or receive the charge from or to the battery. These circuits are used to charge and discharge the battery. A buck converter is used to charge the battery, and a boost converter is used to discharge the battery and send the power to the load when the power level of the wind turbine is low. The transistor in a buck converter is switched on and off with the appropriate duration to charge the inductor and reach the output voltage to the reference value.

**Boost Converter** - In order to charge and discharge the battery, two separate converters were used. A boost converter was used to increase the output voltage of the battery to higher values and maintain the bus voltage at the required level. This circuit provides a path for the power from the battery to the bus. The design values of the circuit are L=1mH, and C=1000µF to minimize the current and voltage variations to values less than 0.1A and 0.5V. R resembles the load, which is connected to the main DC bus, and Vdc is the battery unit. An IGBT transistor was used to switch the circuit on and off. The boost circuit is shown in Figure 19. This circuit can provide non-inverted voltages from the source voltage up to infinite, in theory.

![Figure 19, Boost power converter](image)

**Figure 19, Boost power converter**

**Buck Converter** - To be able to charge the battery, a buck converter was designed and built on the same board. The circuit is shown in Figure 20. The buck circuit is connected from the main DC bus (load) to the battery unit and can provide non-inverted voltages from the bus voltage to 0 volts.

![Figure 20, Buck power converter](image)

**Figure 20, Buck power converter**

**Circuit Integration and Board Design**

The circuit board was designed using the Ultiboard program that can be directly used by the circuit board machine available at the Purdue School of Engineering and Technology. All the circuitry is to be placed on one board; that requires extensive planning to route all the connections around each other without crossing connections. The machine requires a 20-mil clearance to allow for the width and
inaccuracy of the chisel tip. The board has a copper bottom that needs to have copper chiseled away to form the connection lines. Full load current will flow through the chip so associated connections require a larger amount of size to handle the current. Multiple reroutes have been necessary to accommodate changes to the circuitry and connections. The views of the bottom of the board with all connection lines and the top of the board with the components are shown in Figure 21.
Transistor Driver Circuit

Voltage regulation and electrical insulation

This circuit takes an input from the monitoring hardware, dSPACE. The inputs go through an opamp chip that simply provides electrical insulation. Two of the available six inputs were used on the chip, one for each input signal from dSPACE. Electrical insulation is needed because an electrical variance from the inputs can damage sensitive electronics downstream. The signal then goes through an optical coupler. This chip encases an LED and a photodiode which provide even better insulation with no actual electrical connections. The signal then goes through a voltage regulator that sets the output signal to 15Vdc for the control circuitry at the same frequency as the input signal. One opamp chip and two each of the optical couplers and voltage regulators were used; one for the buck signal and one for the boost signal. The circuit was prototyped on a breadboard to ensure proper operation. Initial testing was done with an input from the Phillips function generator to ensure the output was correct. A basic diagram of the circuit is shown in Figure 22, and the test results are shown in Figures 23-26 where several combinations of input voltages at different frequencies were experimentally verified. The input graphs are on the left and the output graphs on the right. The output signal voltage is always ± 15 Vdc or 30Vdc peak to peak. The output signal frequency is always the same as the input signal frequency. This was the expected outcome with the tests confirming the theory.

![Figure 22, Transistor driver circuit with optical interfaces and converters](image-url)
Figure 23, 1 kHz 5.6V input

Figure 24, 500 Hz 7.2V input

Figure 25, 1 kHz 8.3V input

Figure 26, 500 Hz 18.2V input
Task 6: Supervisory Controls

The main supervisory control unit controls the bus voltage by charging and discharging the battery as required. In high-speed wind situations, when the amount of energy captured from the wind is high, the supervisory control unit charges the batteries, and at low wind speed, it will discharge the battery to provide enough power for the load. The bus voltage is the main reference point for the controller. The wind emulator’s output is a DC voltage that increases as the rotation speed increases. This wind generator is connected to the main bus with a diode to prevent the power from flowing back to the source when the wind speed drops. The battery control unit is a subsection of the supervisory control unit that is shown with buck control and boost control labels. The main unit to control the power of the battery in the charge and discharge sequences is the current limiting unit.

Control system operation

The battery control unit continuously measures the bus voltage. As this voltage drops below a set point, the boost controller is turned on to maintain the bus voltage at the required level (14V in this research). As the wind speed increases, the voltage output of the generator increases, and when it exceeds 15 volts, the battery discharge unit is turned off. Simultaneously, the battery charge unit is turned on to charge the battery at a controllable rate. The overall control system is shown in Figure 27.

Current Limiting Circuit

The current limiting circuit and charge-discharge enabling circuit are both shown in Figure 28. As the figure shows, set-reset devices are used to limit the current in both charge and discharge situations. As the current in either case exceeds the set point, current determined by the user, the unit is turned off. However to start the charge and discharge from the latch situation, the unit is turned on by a pulse at a certain rate. The unit operates at the desired rate with PWM controllers as long as the current does not exceed the set point. This logic is true for both charge and discharge circuits.
In addition, this circuit can select the charge and discharge situations by a set and reset unit. The default is set to buck, i.e. charging the battery. However, as the bus voltage increases, the battery charge current set point can be increased to a higher number. As the bus voltage decreases, the battery charge unit will reset, and the boost converter will be turned on to discharge the battery and maintain the voltage.

**Figure 28**, Current limiting logic individually controllable for charge and discharge

**Battery Charge Control Unit**

A buck converter is required to direct the current from the bus to the battery by lowering the bus voltage at the battery terminal. The PWM technique was used to control the buck converter. A buck DC-DC converter was designed and manufactured to lower the bus voltage when it exceeded a predetermined threshold. To charge a 12 volt battery with a high bus voltage, a buck converter must regulate the voltage to a lower number close to the battery terminal voltage. This voltage should be slightly higher than the nominal voltage of the battery to let the current flow to the battery and charge the unit. High voltages increase the risk of high currents, battery temperature increase, and explosion. A PID controller was used to provide an acceptable overshoot and settling time to reduce the transients. Switches were used to generate the PWM pulses of 10 volts.

**Figure 29**, PWM buck control unit with enable/disable input

A buck-enable signal can be received from the current limiting unit and has the control advantage of minimizing the output current from the unit and enabling the charging of the battery.
Boost Control Unit

A boost converter is required to increase the voltage at the bus to maintain the minimum voltage and direct the current from the battery to the load. The PWM control technique was used to control the output voltage of the boost converter. The converter was designed and manufactured with the control logic shown in Figure 30. A PID controller was designed to achieve a controllable performance as required by the application. The bus voltage in this research was set to 14 volts. Therefore, the switching sequence was set to increase the amount of energy captured in the on-time of the IGBT switch and release it when the switch was off. The longer the on time, the more energy captured. As a result, the output voltage of the unit increased to the desired values.

![PWM Boost Circuit Control Schematic](image)

Figure 30, PWM boost circuit control schematic as used in Matlab/Simulink unit with enable/disable signal.

The boost-enable signal can be received from the current limiting unit and has the control advantage of minimizing the output current from the unit and enabling the discharging of the battery.

Task 7: Experimental Results

As illustrated in the previous section, the output voltage of the wind turbine increases as the wind speed and rotation of the generator’s shaft speeds up. In this situation, the control unit is required to take proper action to charge or discharge the battery unit to capture most of the wind energy and regulate the output power at the load. In this regard, the following experiments at different wind speeds were conducted to demonstrate the operation of the supervisory control unit in general and its sub-controllers for buck (battery charging) and boost (battery discharging).

**Stationary condition**

At the stationary condition, the wind speed was zero. Therefore, the wind generator could not generate any power, and as a result, the battery provided the power to the load. In this situation, the boost converter was activated to increase the battery terminal voltage and maintain the bus voltage at the required level. Figure 31 demonstrates the performance of the boost converter. The pulses were generated from the PWM controller, and since the operation mode was in boost mode, the buck pulses were not present. As the figure demonstrates, the output voltage of the boost converter is fixed at 14V, and since the battery provided all the power to the load, the battery terminal voltage dropped from 12 volts to 9.5 volts average. The battery state of charge was low in this test. Since the boost circuit provides power for the telecommunication applications, a high performance was expected. In the design of the power converter,
the current variation and output voltage variation were intentionally limited to low variations to result in low ripples and smooth, continuous operation.

![Battery Control Unit Response at 0 rpm Wind Generator](image)

**Figure 31, Voltage profile, and PWM control signals at 0 rpm**

780 and 1200 rpm generator speed operations

As the generator sped up, the current contribution from the wind generator increased. The effect of generator contribution could be shown on the battery voltage output. The terminal voltage of the battery increased from 9.5V to 10.5V in this situation. As shown, the controller can maintain the bus voltage to 14V fixed (Figures 32, 33). The voltage ripple is very limited and the operation is smooth.

![Battery Control Unit Response at 780 rpm Wind Generator](image)

**Figure 32, Voltage profile, and PWM control signals at 780 rpm**
At 1693 rpm, the generator can provide power for the load. Therefore, the supervisory control keeps the battery in stationary mode and lets the generator provide the power to the load. As shown, the terminal voltage of the battery is increasing to a nominal value. Since the state of charge is not 100%, the terminal voltage is not a nominal value, or 12V (Figure 34).

At 1800 rpm, the voltage of the generator terminal increases. Therefore, it increases the voltage of the bus above the threshold to which the charging circuit can be set. As the buck circuit is turned on, the battery is charged at a certain rate to increase its lifetime. Figure 35 shows the charging sequence of the battery and the voltage profiles in the charging conditions. The battery voltage is set to 12.6V to allow enough current to get to the battery. This value can be increased as the capacity of the battery increases or the state of charge decreases dramatically. Buck pulses are generated from the buck PWM control unit.
The bus voltage is floating with the generator voltage output to higher values, but it is limited to the boost voltage if it drops below 14V. At a higher rotation speed, the output voltage increases, but the charging circuit keeps the terminal voltage of the battery constant. The charging profiles of the battery at different generator speeds are shown in Figures 35-37.

Figure 35, Voltage profile, and PWM control signals at 1800 rpm

Figure 36, Voltage profile, and PWM control signals at 1997 rpm
 transient response analysis

The static operation of the supervisory control at a constant wind/generator speed was demonstrated in the previous section. The dynamic operation of the wind generator is shown in this section. The dynamic operation occurs when the generator experiences varying wind speeds. The supervisory control unit is expected to adjust the bus voltage in the boost mode and the battery terminal voltage in the buck mode. The switching from one mode of operation to the other creates a controller windup error. The transient response of the controller should provide a smooth transition from charge to discharge and vice versa. The controller should be equipped with anti-windup logic to shorten the transient response and to prevent unregulated charge and discharge voltages. Integrator saturation is the main reason for the windup problem. To prevent this, upper and lower limits were selected for the integrator. The resulting transient was very short, and variations were limited as the experimental results demonstrate in Figure 38.

Figure 38, Transient response from charge to discharge when the wind generator speed varies, PWM control signals for charge and discharge

The diagrams show the results of the controller. The finished controller has achieved the control goals and specifications.
3. Conclusion

This report focused on the sizing procedure of the wind turbine, battery unit, charge estimation, and charge control system for a standalone hybrid-wind power system. The power system was designed to feed very sensitive communication devices in cell phone towers. The details of the research on the hardware design and the supervisory control were also included. A supervisory control unit can manage the charge-discharge of the battery unit based on the availability of power harvested from the wind turbine generator. Successful operation of an integrated charge control unit was also demonstrated at high-speed and low-speed winds and in the generator shaft. The charge control unit was designed in order to be controlled by dSPACE fast prototyping device. Novel voltage and current limiting control circuits were designed, manufactured, and implemented for experimental demonstration of the control system operation. The charge control unit had a boost converter to discharge the battery and maintain a predefined voltage at low wind speeds. A buck converter was designed to keep the battery charged. This converter could charge the battery at a specified rate (Current and Voltage) and could adjust accordingly as the state of charge in the battery varies.

As a result of this project, the sizing procedure for cell phone tower applications was clearly defined and experimentally verified for components such as wind turbines and battery units, and for the design and implementation of units such as battery charge/discharge units and supervisory controllers.

4. Publications

2 posters and 2 oral presentations have been presented based on the research conducted with this funding. One conference paper and one journal transaction are being written to be published in IEEE conferences and journal transactions.

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