Lead Acid Batteries Modeling and Performance Analysis of BESS in Distributed Generation

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11/19/2012

A thesis report submitted to the School of Engineering and Energy, Murdoch University, in partial fulfilment of the requirements for the degree of Bachelor of Engineering
Acknowledgement
I would like to acknowledge my thesis supervisor, Dr. Greg Crebbin for providing guidance and for helping me to define my research topic, constantly asking me the tough questions. Authors, who have made past contribution to this topic of research and in turn, helped me to formulate my own thesis understanding. Finally, to my family and friends who have provided much needed moral support at a difficult and challenging time of my life. Completing my thesis is for you.

Stand on the shoulders of giants
Abstract
In this thesis, a methodology to accurately determine the state of charge (SOC) of a lead acid battery is proposed by calculating the integration of the net current flow through the battery at given time, t. Using an electrical circuit diagram of the lead-acid battery model; will run a simulated model of a lead acid battery and its charging or discharging characteristics are estimated based on the input values provided by manufacturers’ or user specifications.

Using the data found, an optimum state of charge (SOC) was determined and a battery energy storage system (BESS) was sized accordingly. A simulation of a peak load scenario was conducted and a system performance analysis was carried out on the BESS connected to a micro-grid system. An investigation into the transient voltage stability at a peak load condition was conducted to compare the response of the battery bank and a diesel powered generator in ability to cope with increase in the load demand.

Furthermore, an investigation into four types of control strategies for a distributed generation system was proposed with some predicted outcomes analyzed. It was found that operating the BESS as a secondary control mechanism to a primary diesel generator was the optimum control set-up. Further investigation into the levelized cost of energy (COE) would be required to conclusively determine these findings.

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Chapter 1

1.1 Introduction
Electro-chemical batteries are of great importance to electrical power systems due to their ability to capture and store energy and to immediately dispatch that energy to meet electrical demands of a grid. Some other main uses of batteries are:

- Uninterruptable Power Supplies (UPS), commonly found in banks, offices and hospitals where an alternative to undesired disruption to electricity supply is required.
- Battery Energy Storage Systems (BESS) that are connected to power grids with the sole purpose of compensating active and reactive powers.
- Hybrid Electric Vehicles (HEV) where batteries are used to capture and store electrical energy for transportation.

Despite the growing use and importance of batteries, there is a distinct lack of battery models that are, expressed in a way that is understandable to an electrical engineer such as in circuitry diagram or electrical network single line diagram.

This project aims to investigate the dynamic behaviour of a model for a lead acid battery that is commonly found in renewable energy systems. The model is then used to predict a battery banks response to peak power demands in a type of distributed subsystem commonly referred to as a micro-grid. A micro-grid is a portion of the power system which includes one or more distributed generating units capable of operating either in parallel with or independent from a large network distributor.

1.2 Thesis Objective
The purpose of this thesis is to develop a model of a lead acid battery that simulates an actual battery performance under charging and discharging conditions. Using the model, an optimized discharge and charging cycles to achieve a larger life expectancy of the battery will be investigated before being implemented in the model of a battery bank typically found in an electrical subsystem also referred to as a micro-grid. This thesis also intends to discover and investigate:
• Current understanding of measuring and optimizing battery SoC performance,
• The purpose and benefits of installing a battery bank in a distributed generation network,
• Methods of using the battery bank to improve micro-grid stability, in particular analysis around the battery bank control and dispatch strategies.
• Simulation study of peak power loads with a battery bank connected.

1.3 Thesis Layout
The following chapters of this thesis are organized as follows;

Chapter 2: Will discuss the background of modeling the lead acid battery by using mathematical models; this model will be evaluated in Simulink based on Matlab software language.

Chapter 3: Will analyze the SimScape™ lead acid battery model demo found in Matlab. An electrical circuit diagram was also developed to verify that the simulation of the SimScape™ model is a reliable indicator of battery performance.

Chapter 4: Will discuss the implementation of modeling a battery bank in a distributed generator network. This chapter will also cover how the transient analysis was set up and conducted in PowerFactory.

Chapter 5: Will cover the PowerFactory simulation model and how it was developed. This chapter will investigate the findings of peak power load demands and will look into various dispatch strategies for Battery-Diesel hybrid systems found in a distributed power generation network.

Chapter 6: Conclusion of the thesis report. This will also include potential future research to be conducted with the findings of this thesis.
Chapter 2

2.1 Modeling the Battery

Modeling the battery is a useful procedure to conduct when carrying out an investigative study on the behaviour of batteries. There are some benefits of modeling a battery in simulation. It can eliminate time constraints, set-up costs, the process of building an expensive physical test module & enables the user to gain control over external factors or parameters.

That being said, there is an inherent difficulty in modeling batteries to test their design due to the complexity of battery systems and the chemical reactions that occur within the battery. Thus, this limits our ability to properly characterize and define a battery design. This along with the fact that manufacturers rarely share their development techniques, which makes conducting a battery modeling test for battery design a difficult topic to research.

The battery model developed in this project was used to conduct a test of discharge and charge of a battery under standard test conditions while plotting the curves and obtaining the relevant state of charge, current & voltage readings.

2.1.1 Battery Parameters and Terminology

Several parameters are important for modeling a battery [1] these are as:

- **Internal Resistance** which is the resistance within the battery. This type of resistance is caused by the charge and discharge conditions of a battery and relies on the state of charge of a battery [1]. Internal resistances increases as the battery efficiency decreases. The thermal stability will also decrease with respect to the charging energy and more heat will be produced.

- **Self-discharge Resistance** which consists of the resistances brought about by the electrolysis of water at higher voltage levels. Self-discharge resistance is also caused by the slow leakage current experienced at the battery terminals when voltage levels are low.

- **Charge and discharge resistance** \( (R_c \text{ or } R_d) \) which are the resistances linked to electrolyte resistance, plate resistance and fluid resistance [1].
• *Polarization Capacitance* which is a descriptive model of the chemical diffusion that occurs within the battery electrolyte terminals.

• *Terminal Voltage (V)* which is the voltage across the terminals and the load. This voltage changes with respect to the SOC, discharging and charging current.

• *Open Circuit Voltage (Voc)* which is the terminal voltage measured no load is applied [1]. This voltage is constant with the state of charge of a battery as the state of charge increases.

### 2.2 Chemical Operation of a Lead Acid Battery

A typical lead acid battery consists of individual cells compartmentalized by layers of sulphuric acid immersed lead plates. When the sulphuric acid comes into contact with the lead plates inside the cell, a chemical reaction is produced. This chemical reaction occurs depends on whether the cell is experiencing charging or discharging. During a discharge, both of the plates will return lead sulfate. The conduction of electrons from the cathode will re-enter the battery cell at the anode, effectively discharging the battery [2].

**Anode Reaction:**  
\[ Pb(s) + HSO_4(aq) \rightarrow PbSO_4(s) + H(aq) + 2e^- \]

**Cathode Reaction:**  
\[ PbO_2(s) + HSO_4(aq) + 3H(aq) + 2e^- \rightarrow PbSO_4(s) + 2H_2O(l) \]

Subsequent re-charging will place the battery back into a charged state. Which changes the lead sulfates into lead oxides. The charging process is driven by the electron transfer from the anode into the cathode [2].

**Anode Reaction:**  
\[ PbSO_4(s) + H(aq) + 2e^- \rightarrow Pb(s) + HSO_4(aq) \]

**Cathode Reaction:**  
\[ PbSO_4(s) + 2H_2O(l) \rightarrow PbSO_2(s) + HSO_4(aq) + 3H(aq) + 2e^- \]

The electrode potential is measured in standard test conditions against a standard hydrogen electrode. The electrical equation for this reaction is as follows [2]:

\[ I_{bat}(V_{bat}) = I_{bat}(V_{cathode}) + I_{bat}(V_{anode}) \]

The cathode voltage for a 12.5 open circuit voltage lead acid battery is +1.69 volts while the anode is -0.358. The battery cell voltage is determined by the voltage difference between the
anode and cathode [2]. The open circuit voltage is therefore 2.048 volts per cell for a lead-acid battery. A 12 voltage battery consists of six cells connected in series. By defining the cathode and anode voltage values, the developed battery model is able to consider the chemical reactions occurring within the battery cells.

2.3 Dynamic equations of the circuit model
The dynamic equations of the lead-acid battery model will provide the circuit with discharging and charging capabilities as a function of time. The equation for the state of charge estimation is given by [6]:

$$SOC = \alpha SOC_c + (1-\alpha)SOC_v$$

(1)

Where;

SOC$_c$ is the Coulomb-counting based SOC;

SOC$_v$ is the voltage-based SOC;

$\alpha$ (\epsilon [0,1]) is the weight factor.

As the state of charge is estimated based on the amount of charge that has been extracted from the battery, the equation for the state of charge as a function of time is calculated as:

$$SOC_c(t) = SOC_c(0) - \frac{1}{Q} \int_0^t I(t) dt$$

(2)

Where;

Q is a constant that relates to the current, I with the state of charge.

The simulation model is based on the inherent iterative process of the SOC equations (1) and (2). There are certain MATLAB functions and blocks that allows for the adaptation of these mathematical equations to be used in a simulation process.
2.4 Electrical Circuit Model

The Simulink model developed in Matlab is based on the research findings of *A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles* [3]. There are three types of electrical circuit battery models that helped in the development of the Simulink model. The types are explained in this literature review.

2.4.1 Battery Electrical Circuit Models

An electrical battery circuit model can be designed as a voltage source connected to a resistor. Figure 1. shows a simplified battery model [1]. The battery model consists of an open-circuit voltage $V_o$, a constant that is equivalent to the internal resistance $R_{int}$, and the terminal battery voltage, $V_t$. This voltage is collected by measuring the open circuit voltage. By connecting the load and measuring the terminal current as-well as the voltage, the value for $R_{int}$ can be obtained. However, the internal resistance is different for discharge and charge conditions [1]. The model discussed here lacks the ability to record any battery dynamics.

![Simple Battery Model](image)

**Figure 1: Simple Battery Model**

To account for the different resistance values under charge and discharge conditions, the circuit is modified as shown in Figure 2 [4] with a short circuit resistance applied across the battery terminals.
Figure 2: Battery Model with Internal Resistance

The battery model in figure 2 consists of two internal resistances; $R_c$ and $R_d$. Due to the diodes in place, either one or the other are active during the charge and discharge process respectively. The parameters for the resistances ($R_c$ and $R_d$) of the model accounts for the loss in energy, including any electrical and non-electrical losses. During the charging and discharging processes, one diode, will provide forward biased current whilst the other is in reversed biased mode. The two diodes are only found within the model design. They have no actual physical presence in a battery.

The model is then required to simulate the chemical diffusion of the electrolytes and the resultant effect of causing transient currents within the battery. This is achieved by adding a capacitor to the model as shown in Figure 3.
Finally, the battery is modeled using a proportional integral feedback loop controller to provide the model with a voltage source that is controlled and in series with a resistance. This newly updated configuration is shown in Figure 4. This will enable the model to simulate a charge and discharge process with the controlled voltage source based on the SOC of the battery.

The controlled voltage source is described by the equation [4]:

$$E = E_0 - K \frac{Q}{Q_{it}} + A \exp(-B \int idt)$$  \hspace{1cm} (3)$$

Where,

$E$ is the no – load voltage (V),

$E_0$ is the battery constant voltage (V),

$K$ is the polarization voltage (V),

$Q$ is the battery capacity (Ah),

$\int idt$ is the actual battery charge (Ah),

$A$ is the exponential zone amplitude (V),
B is the exponential zone time constant inverse \((A\,h)^{-1}\),

\(V_{\text{batt}}\) is the battery voltage (V),

\(R\) is the internal resistance (Ohms) and;

\(I\) is the battery current (A)

![Battery Model with Voltage Control Diagram]

**Figure 4: Battery Model with Voltage Control**

**2.4.2 The Charging State of the Battery** [4], [6] where \(V_P \leq V_{oc}\)

In the case of charging the battery, the simulation has a feedback loop controller on which it compares the difference in pre-defined SOC values to determine whether the battery has reached the lowest specified value of SOC. If the lowest set value is reached, the DC machine will begin charging the battery at a pre-set charge current value. The equation that describes this process of the charge model is given as [3]:

\[
f_1(it, i*, i, \text{Exp}) = E_0 - K \left( \frac{Q}{it + 0.1Q} \cdot i + A \cdot \exp(-B \cdot it) \right) + \text{Laplace}^{-1}\left( \frac{\text{Exp}(s)}{s} \cdot \frac{1}{\text{Sel}(s)} \right)
\]

**2.4.3 The Discharging State of the Battery** [4], [6] where \(V_P > V_{oc}\)

Similar to the charging state of the battery, a discharging state feedback loop controller is also designed to measure the difference in pre-defined SOC values to determine whether the
battery is in a discharge state where \( V_p > V_{oc} \). The equation that describes the discharge process of the model is given as [4]:

\[
f_2(it, i*, Exp) = E_0 - K_1 \frac{Q}{Q-it} \cdot i* - K_2 \frac{Q}{Q-it} \cdot i + \text{Laplace}^{-1} \left( \frac{Exp(s)}{Sel(s)} \right) 0 \quad (5)
\]

The circuit diagram Figure 5 is then modified to incorporate the charging and discharging state of the battery explained by the equations (4) & (5).

![Battery Model with Charging & Discharging](image)

**Figure 5: Battery Model with Charging & Discharging**

### 2.4.4 Model Assumptions

There have been some assumptions made for the simulation model listed below [4]:

- The internal resistance is assumed to be constant during the charging and discharging sequence.
- The parameters for the model are based upon values found from the discharging and charging sequence.
- There is no change with the capacity of the battery or the amplitude of the current.
- Temperature of the battery is not taken into consideration.
- The self-discharging state is not represented; and the battery is also deemed to have no effect on the stored memory.
2.5 Model Validation Process

The model validation had an Error$_{\text{max}}$ of 5% for the charge and discharge current.

The process of simulation was conducted as follows:

<table>
<thead>
<tr>
<th>No.</th>
<th>Simulation process of Simulink Lead Acid battery model</th>
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</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Simulation start button is switched on;</td>
</tr>
<tr>
<td></td>
<td>(1) Simulation run time is set to 36000 seconds</td>
</tr>
<tr>
<td></td>
<td>(2) Data is captured via MATLAB workspace and saved to array file ‘Filename.xls’</td>
</tr>
<tr>
<td>(2)</td>
<td>Battery discharging;</td>
</tr>
<tr>
<td></td>
<td>(1) Battery begins discharge from a SOC of 100%</td>
</tr>
<tr>
<td></td>
<td>(2) Measurement is obtained for voltage, SOC, DC motor speed &amp; armature current.</td>
</tr>
<tr>
<td>(3)</td>
<td>Battery charging;</td>
</tr>
<tr>
<td></td>
<td>(1) DC machine begins charge with a constant current</td>
</tr>
<tr>
<td></td>
<td>(2) Measurement is obtained for voltage, SOC, DC motor speed &amp; armature current.</td>
</tr>
<tr>
<td>(4)</td>
<td>Simulation stops after 36000 seconds</td>
</tr>
</tbody>
</table>

Table 1: Simulink Simulation Process

The simulation was also based on SOC values ranging from 0.4 to 0.8. This was done because the optimum voltage window as-well as the optimum lifetime of a lead acid battery operates within these ranges. Thus, the charge discharge process will start from a SOC of 1.0 and reach 0.4 SOC before the charge process begins at a SOC of 0.4 and stops at 0.8 SOC.
Figure 6: Graph of Voltage and State of Charge

The output plot given in figure 6 was obtained from the scope measurement of the Simulink battery model. As explained, the SOC drops to 0.4 before the DC machine begins charging the battery at a constant current, before cutting off at 0.8 SOC. The discharge and charging process repeats itself for the duration of the simulation and the output voltage is measured. This plot validates that the Simulink Lead-Acid battery model is working as intended.

2.6 Parameters from manufacturers data-sheet
The table listed below contains the parameter data used in the simulation model. A more detailed data-sheet for various analyzed battery parameters can be found in Appendix A.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>FullRiver 12V 150Ah</th>
<th>Trojan 12V 150Ah</th>
<th>Trojan 12V 200Ah</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Voltage $E_0$ (V)</td>
<td>12.5</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Internal Resistance (Ohms)</td>
<td>0.025</td>
<td>0.035</td>
<td>0.035</td>
</tr>
<tr>
<td>Constant Voltage Charge K (V)</td>
<td>0.23</td>
<td>0.25</td>
<td>0.28</td>
</tr>
<tr>
<td>Discharge Current (A)</td>
<td>25.6</td>
<td>26.5</td>
<td>26.5</td>
</tr>
<tr>
<td>Nominal Capacity $B$ (Ah)$^{-1}$</td>
<td>150</td>
<td>150</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 2: Battery Parameters
2.7 Discussion on Simulink Model and Simulation Results

Figure 7 displays the block diagram to simulate discharge and charge process of a lead acid battery. The simulation was developed in Matlab Simulink. The simulation is made out of four distinct parts, the first part is the pre-defined battery model developed by Matlab. Second part is the DC machine that charges the battery by a constant charge current. The third part is the feedback loop controller that takes the measurement of the State of Charge at different intervals and compares it to pre-defined SOC upper and lower limits, which as explained earlier is set to 0.8 and 0.4 respectively. In turn, the controller has control over the decision to charge the battery via the DC machine. The fourth and final part is the data acquisition where the output is fed to a scope and the simulation output feeds to workspace; and subsequently saved as an excel spreadsheet file for independent analysis of the data collected. A detailed explanation of each individual component can be found in Appendix C.
2.8 Analysis of Simulation Results

2.8.1 Depth of Discharge (DOD) (%) refers to how much capacity is withdrawn from the battery. This withdrawn depth is given as a percentage. Deep cycle batteries such as large capacity lead acid batteries are able to withstand a depth of discharge of up to 80%. Battery life is directly related to the depth of discharge and the number of charging cycles it experiences over its lifetime.

2.8.2 Correlation of Voltage of Battery and Depth of Discharge Rate

According to the *Solar International Handbook* [3], the rate at which the battery is discharge directly affects the capacity. If the battery is discharged too quickly, the capacity is significantly reduced and the opposite occurs to the capacity when the battery is discharged over a long period of time. In the plot of voltage vs discharge time above, shows the different discharge rates for four manufacturers’ battery nominal voltages over a time period of 36000 cycles per second. The nominal voltage level over time is significantly affected by the rate of discharge with the nominal voltage experiencing a drastic reduction after a period of time. This has also been validated and compared to manufacturers expected results found in Appendix A.
2.8.3 Effect of Temperature on Battery Capacity

This test did not take into account the temperature, a study has shown [7] that batteries are sensitive to the environment and are particularly affected by temperature. Although the battery capacity decreases with lower temperatures, the battery life actually increases with colder temperatures. Manufacturers predict a 50 percent loss in battery life for every 15 degree F above the standard 77 degree cell temperature [7]. Extremely cold temperatures can have a detrimental effect on the battery by freezing and inhibiting the movement of electrolytes.

2.8.4 Battery State of Charge

![Plot of Voltage (V) vs SOC (%/100) at different Discharge Current](image)

The battery nominal voltage level is related to the current state of charge of a battery. As shown by the graph above, the nominal voltage level is significantly higher with every increase in battery state of charge. This suggests that having a battery with a higher state of charge is responsible for higher voltage levels and is consistent with all the batteries across the board.
2.8.5 Amp Hour Capacity

Deep Cycle batteries are rated in terms of Amp Hour (Ah). This signifies the amount of amperage a battery can hold within an hour or $amp \times hour$. Figure 8 obtained from the Simulink battery model scope displays the batteries nominal voltages of four different batteries at four particular ampere-hour rates. Another reason for the rate to be specified is because of the Puekert Effect that batteries experience. The Puekert Law is defined by the increased rate of discharge and subsequent decrease in the battery's available capacity [5]. Factors such as depth of discharge, rate of discharge, temperature, age, and charging will have an effect on battery capacity.

The watt hour (wh) capacity of a battery is the product of amp hour capacity and battery voltage. Adding batteries in series increases the energy storage by increasing voltage while the
amp hour capacity remains constant. Conversely, adding batteries in parallel increases the energy storage by increasing the amp hour capacity whilst keeping the voltage constant.

2.8.6 Peukert Effect for various battery manufacturer specifications

Battery capacity is a function of the time and rate a battery is discharged. In addition to this, a battery’s capacity is reduced as its discharge current increases. This reduction in battery capacity was documented by Peukert in 1897 [5]. The Peukert effect is a description of how the battery capacity is directly affected by the speed of which a battery is discharged. Battery manufacturers specify battery capacity for different periods of discharge.

Peukert also figured out that the capacity of a battery can be found by plotting the discharge rate.

\[ C = i^K t \]

Where;

\( C \) = battery capacity at 1amp discharge rate.

\( i \) = discharge current &,

\( K \) = puekert coefficient determined by the battery manufacturers specification datasheet discharge curves, it is typically between 1.1 and 1.3.

\( t \) = discharge time

Refer to figure 9,
Figure 9: Graph of Puekert Effect
Chapter 3: Detailed analysis of Matlab Simscape™ Lead Acid Battery Demo

There exists a simulation model of a lead-acid battery cell in Simscape™ language based on the powerful mathematical program, Matlab. An in-depth description on how to operate this model can be found in Appendix B of this thesis. This model consists of individual mathematical components that when combined together creates a dynamic and accurate simulation of a lead acid battery. This demo is very useful in modeling different battery scenarios due to the ability to change the parameter values to whatever you require them to be. A detailed analysis of the software capability and how it can help to determine different battery manufacturers SoC and other important battery measurements was carried out.

3.1 Simulink Model Structure of a lead-acid battery cell

![Figure 10: Simscape™ Battery Cell Model](image)

An explanation of the various components can be found in Appendix B.
3.2 Battery Equivalent Circuit
An ICAPS battery model was developed to provide an equivalent electrical circuit to the Simscape™ model. The battery circuit equations in Figure 10 are based on a simple non-linear equivalent circuit of the simulink model of Figure 9. The equivalent circuit models the behaviour seen at the terminals of the battery [11]. The circuit is broken into two branches; the first branch simulates the battery dynamics under most conditions, and a parasitic branch simulates the battery behaviour at the end of a charge [11]. Further description for the simulink model and equations developed for use in the Matlab based Simscape™ lead-acid demo can be found in Appendix C.

Figure 11: ICAPS circuit diagram of Battery Cell
3.3 Parameters for the circuit

The parameter values for the circuit were based on manufacturer data found in Appendix A. The input values for the circuitry that was entered into the ICAPS and SimScape™ models are listed in Table 3 below.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>[V]</td>
<td>Open Circuit Voltage</td>
<td>12.5</td>
</tr>
<tr>
<td>CellCapacity, C1</td>
<td>[F]</td>
<td>Capacity per cell</td>
<td>50</td>
</tr>
<tr>
<td>R1</td>
<td>[ohms]</td>
<td>Resistor 1</td>
<td>0.008</td>
</tr>
<tr>
<td>R2</td>
<td>[ohms]</td>
<td>Resistor 2</td>
<td>0.12</td>
</tr>
<tr>
<td>Diode</td>
<td>[int]</td>
<td>Forward biased Diode</td>
<td></td>
</tr>
<tr>
<td>Rp</td>
<td>[ohms]</td>
<td>Diode resistor</td>
<td>0.01</td>
</tr>
<tr>
<td>R0</td>
<td>[ohms]</td>
<td>Nominal voltage resistor of source</td>
<td>0.9</td>
</tr>
<tr>
<td>V2</td>
<td>[V]</td>
<td>Nominal voltage</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 3: Parameters for SimScape & ICAPS model

3.4 Results

The results below are plots for the charge load current, terminal voltage, state of charge, depth of charge and temperature of the manufacturer lead acid battery based on the SimScape™ Matlab simulation. A comparison analysis of the SimScape™ results was conducted with the electrical circuit designed in ICAPS simulation. The results were validated by comparing to manufacturer data-sheets in Appendix A and a previously investigated lead-acid battery discharge research paper submitted to a prominent engineering journal magazine [12].
Figure 12: SimScape Battery Model Scope

Scope 1. Charging/Load Current (A)  
Scope 2. Terminal Voltage (V)  
Scope 3. State of Charge (SOC)  
Scope 4. Depth of Charge (DOC)  
Scope 5. Temperature (degrees C)
3.5 Discussion on ICAPS and SimScape™ models

The results between the ICAPS model and SimScape™ model had some variation; and is partly due to the electrical circuit design in ICAPS having less input parameters than the SimScape™ model. The simulation run-time is also different with the SimScapeTM model running over a long period of time, whereas the ICAPS model captures instantaneous circuit reaction. Thus, they both could be used for different purposes; with one analyzing the performance of a battery over a period of time, and the other analyzing the instantaneous battery performance [13].

SimScape™ lead acid model in Matlab is an accurate and well-developed simulation that is able to display dynamic characteristics of the terminal voltage, state of charge, depth of charge and temperature over any certain period of time. The user-friendly functions found in the model enables for user customization for just about any known criteria of a lead acid battery found in an electrical circuit.
Chapter 4

4.1 What is a battery bank?
A battery bank consists of a group of batteries linked together to produce a large enough voltage output and ampere hour reserve to provide power to an application that requires electrical energy. A battery bank can be made out of a large number of batteries connected together in series or in parallel. The way the batteries are connected together will depend upon whether it is intended to increase the voltage or ampere hour reserve. By connecting the batteries in series, the voltage output will double whilst the ampere hour reserve remains the same. Likewise, connecting the batteries in parallel will double the ampere hour reserve, whilst the voltage remains the same. A combination of both series and parallel batteries will be required to form a usable and powerful battery bank.

The role that a battery bank plays in an energy system is normally as a point of capture and subsequent storage of energy for later use. This thesis looks to analyze some of the benefits of a battery bank by modeling a micro-grid and analyzing the simulation processes.

4.1.1 Usages of Battery Bank in Power Systems:

A battery bank can be used to provide Uninterruptable Power Supply (UPS) for systems where emergency and redundancy power systems are required in the event that the mains power is disrupted. UPS systems are usually found in banks, hospitals, data communication centres and various other locations where an un-interrupted power supply is required. The primary reason why battery banks are used to provide UPS is their capability to supply near-instantaneous power and protection to delicate systems. The disadvantages of a UPS are the high associated costs and the fact that most UPS systems can only supply power for a relatively short amount of time; but usually this is enough time to get a standby power generator running or to properly shut-down the system for protection.

Another scenario where battery banks are found; and what is also relevant to the research of this thesis is in embedded power generation systems. The power grids of the future are fast integrating with distributed power generation systems. Intermediate renewable power
generation technologies such as photovoltaic and wind turbine power plants are requiring some sort of energy capture and storage medium in order to increase its reach and maximize their potential gains. A properly designed battery bank can provide an energy storage system solution to renewable power energy systems by capturing excess produced power, also known as peak power shaving and releasing this excess power back into the grid when the renewable energy systems are not in operation.

4.1.2 Advantages of Battery Bank in Micro-grid

- Battery banks are a reliable back-up power source to AC critical loads.
- Battery banks can be used to capture and store excess energy produced by power generation systems.
- Battery banks require little to no maintenance, especially valve-regulated lead acid (VRLA) batteries.
- No fossil fuel is required to power the battery banks thus this can help to lower carbon dioxide emissions.

4.1.3 Disadvantages of Battery Bank in Micro-grid

- They are expensive to build from the ground up and requires plenty of power electronic components, primarily DC to DC step-up voltage converter, bi-directional 3-phase inverters, charge controllers, and sophisticated power control.
- They have a limited life-span that is dependent upon the optimization processes to prolong the amount of years at a level that is beneficial to the power system.
- They are a potential fire and explosion hazard with harmful chemicals within the batteries may cause corrosion or poisoning if left to dissipate with the environment. Consequently, the battery bank is only able to meet low current load demands as protective measures against such dangerous hazards.
4.2 Introduction to the Battery Energy Storage System

A BESS stands for Battery Energy Storage System [14]. The BESS proposed in this thesis consists of a battery bank made out of Valve Regulated Lead Acid (VRLA) batteries. The manufacturers data for the Trojan 12V, 150Ah batteries was used to develop a 24V, 5000Ah battery bank; a sizable power generation BESS unit. The components that make up this battery energy storage system consist of a DC-DC step up converter, an AC-DC bi-directional inverter, fuse boxes and circuit breakers. All components have to be regulated and specified based upon the relevant standards such as AS/NZS 3000:2007 - wiring rules and AS/NZS 5033:2005-installing grid connected systems and possibly also AS4777 and any standard associated with UPS systems and batteries. Such a BESS unit will costs in excess of tens of thousands of dollars, thus a simulation model can assist in determining and optimizing expected performance gains and numerous other potential issues with the system without spending a lot of time and money.

The Table 4 listed below gives an overview of the components proposed to build a BESS.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>24V, 5000ah Battery Bank</td>
<td>33 parallel batteries connected in two series.</td>
<td>66 x Trojan 12v, 150ah batteries</td>
</tr>
<tr>
<td>DC-DC step up boost converter</td>
<td>The converter will step up the BESS voltage to nominal grid voltage.</td>
<td>1 x boost converter</td>
</tr>
<tr>
<td>AC-DC inverter</td>
<td>The inverter will change the signal from DC to AC and match the phase of the load.</td>
<td>1 X SMA off-grid Inverter</td>
</tr>
<tr>
<td>Battery charger</td>
<td>Charge the battery depending on the SOC at any given time</td>
<td>1 x Battery charger with SOC control</td>
</tr>
<tr>
<td>Fuse boxes</td>
<td>Junction boxes to be installed at each of the series connection.</td>
<td>2 x junction boxes</td>
</tr>
<tr>
<td>Circuit breaker</td>
<td>Disconnects the battery bank at the incoming AC supply</td>
<td>1 X 3 pole circuit breaker</td>
</tr>
</tbody>
</table>

Table 4: Components of BESS
4.3 Definition of Distributed Generation
The definition to describe distributed power generation is a topic that has become a debatable discussion on what constitutes distributed generation [15]. In most cases, distributed generation stands for a power source that is connected to the end-user side of the meter and or a locally distributed generation network. In such cases, the utility and power generation companies aren’t usually the owners of distributed power generation. The power is not centrally dispatched and this increases the intricacy of power grid connections. A common usage of distributed generation that illustrates this is in Combined Heat & Power (CHP) system and such systems are usually located at industrial sites; where the industrial customer is connected to the transmission network and subsequent user-side of the meter. Another common scenario where one would not entirely define as a distributed generation situation is when a wind farm is directly connected to the transmission network, due to the limited capacity of local distribution network, the wind farm exports back to the transmission network any excess energy produced.

4.4 Modeling Battery bank in power systems
There are various methods of investigating a battery bank model in power systems. The most common method used in simulation models consists primarily of a DC voltage source connected to either a converter or an inverter. The values for internal resistance and nominal voltage should be incorporated into the model and should also be able to measure any simulation outcomes for detailed analysis.
Chapter 5

5.1 PowerFactory Simulation of Battery in micro grid conditions: Modeling and Control

DlgsILENT PowerFactory version 14.1 was the software used to simulate a battery bank in micro grid conditions. A balanced RMS simulation method was used because it offers a wide range of options into simulating various dynamics in electromechanical, control and thermal devices in symmetrical operation.

The Battery Energy Storage System (BESS) stores energy during off-peak periods or at low load demand and transmits energy back into the system during peak periods or at high load demand. Thus, a BESS can effectively replace a diesel powered generator as the ideal back-up or spinning reserve system. A BESS becomes even more attractive option in micro-grid or remote area power systems where connection to the main grid may be too much of a hassle or an expensive cost to carry out.

A well-defined research study into the amp-hour capacity of the BESS is of importance in terms of finding out whether the usage of a BESS can be a viable alternative to an active power peaking station [19]. The PowerFactory simulation will be primarily focused on the finding of a simulation of a battery bank under micro-grid conditions. The single line diagram model developed in PowerFactory v14.1 will measure the voltage of the battery and the subsequent values for optimum state of charge, battery capacity, nominal voltage and internal resistance values based upon the battery measurements at continuous discharging currents obtained from the previously investigated Simulink MATLAB model. A simulation was conducted to measure the load leveling profile and was used as a comparison to the measured voltage and current profiles previously obtained from Simulink model from MATLAB.
5.1.1 Model of the Diesel Generator in PowerFactory

Synchronous generators have built-in models in PowerFactory. The parameters and the rated values of a generator can be entered into a model manually. The generator used for this thesis is a 1.02 MVA rated Diesel Generator (Diesel_Gen) with a nominal rated power of 0.816 MW.

![Diagram of Diesel Gen Terminal](image)

Figure 13: PowerFactory Diesel Generator model

The method of entering values into the PowerFactory model of the diesel generator was based upon entering values for reactances and resistance of the motor equivalent circuit. This was done because it was much easier to obtain reactance and resistance values for a diesel generator than it was for obtaining values for the torque and slip curve characteristics. PowerFactory will automatically optimize the equivalent circuit once values of have been entered into the model. The calibration parameters for the diesel generator are listed in Table 5.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>[MVA]</td>
<td>Rated power output</td>
<td>1.02</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>[KV]</td>
<td>Nominal bus and terminal voltage</td>
<td>32KV</td>
</tr>
<tr>
<td>PN</td>
<td>[MW]</td>
<td>Prime mover rated power</td>
<td>0.816</td>
</tr>
<tr>
<td>Ra</td>
<td>[pu]</td>
<td>Armature Resistance</td>
<td>0.2</td>
</tr>
<tr>
<td>Xd</td>
<td>[pu]</td>
<td>Reactance</td>
<td>2.0</td>
</tr>
<tr>
<td>Xd'</td>
<td>[pu]</td>
<td>Reactance</td>
<td>0.85</td>
</tr>
<tr>
<td>Xd''</td>
<td>[pu]</td>
<td>Reactance</td>
<td>0.2</td>
</tr>
<tr>
<td>Tdo'</td>
<td>[s]</td>
<td>Torque</td>
<td>0.01</td>
</tr>
<tr>
<td>Tqo</td>
<td>[s]</td>
<td>Torque</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Table 5: PowerFactory Diesel Generator Parameters
5.1.2 Modeling of the BESS Controller in PowerFactory

As discussed earlier, PowerFactory version 14.1 does not come with a pre-designed battery energy storage model. Thus, a battery energy storage system was developed consisting of two vital components; the electrochemical storage component and a rectifier or inverter that transforms the voltage from DC to AC and vice versa. The rectifier or inverter is usually based on a voltage source converter (VSC). PowerFactory has a readily available standardized model of the voltage source converter (VSC) in the form of a Pulse Width Modulator (PWM)/Inverter.

![Figure 14: PowerFactory PWM Converter Model.](image)
5.1.3 Modeling of the converter/inverter in PowerFactory

The PWM inverter converter in PowerFactory has two inputs; the (id_ref) which represents the real part of the reference current and (iq_ref), which represents the imaginary part of the reference current. The (id_ref) determines the active power output of the converter, while (iq_ref) determines the reactive power of the converter. The calibration of the parameters for the PWM converter is listed in Table 6:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Voltage</td>
<td>[kV]</td>
<td>Rated AC output voltage.</td>
<td>0.4</td>
</tr>
<tr>
<td>DC Voltage</td>
<td>[kV]</td>
<td>Rated DC input voltage</td>
<td>0.6</td>
</tr>
<tr>
<td>Rated Power</td>
<td>[MVA]</td>
<td>Power of the converter</td>
<td>5</td>
</tr>
<tr>
<td>Control Mode</td>
<td>-</td>
<td>Control mechanism of the system</td>
<td>Vac-Vdc</td>
</tr>
<tr>
<td>Reactive Power limits</td>
<td>[pu]</td>
<td>The minimum and maximum limit of reactive power compensation</td>
<td>Min -1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MVar_{min} -5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MVar_{max} 5</td>
</tr>
</tbody>
</table>

Table 6: PowerFactory PWM Inverter Converter Parameters
5.1.4 Modeling of the BESS in PowerFactory

![Battery Terminal Cub_2](image)

Figure 15: PowerFactory Battery Model

The model parameter for the battery energy storage system is based upon the optimized SOC, nominal voltage and internal resistances discovered in the Simulink battery model. The input parameters were then sized accordingly; based upon manufacturer data-sheet to model a battery bank as a large component.

The calibration of the parameters for the battery model is listed in Table 7:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SoC</td>
<td>[int]</td>
<td>State of charge at initialization</td>
<td>0.5</td>
</tr>
<tr>
<td>CellCapacity</td>
<td>[Ah]</td>
<td>Capacity per cell</td>
<td>480</td>
</tr>
<tr>
<td>u_min</td>
<td>[V]</td>
<td>Discharged Voltage</td>
<td>12</td>
</tr>
<tr>
<td>u_max</td>
<td>[V]</td>
<td>Charged Voltage</td>
<td>13.85</td>
</tr>
<tr>
<td>CellsParallel</td>
<td>[int]</td>
<td>Amount of parallel cells</td>
<td>60</td>
</tr>
<tr>
<td>CellsInRow</td>
<td>[int]</td>
<td>Amount of cells in row</td>
<td>65</td>
</tr>
<tr>
<td>Unom</td>
<td>[kV]</td>
<td>Nominal voltage of source</td>
<td>0.9</td>
</tr>
<tr>
<td>RiCell</td>
<td>[ohm]</td>
<td>Internal resistance per cell</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 7: PowerFactory Parameters of the Battery Model

5.1.5 Load Profile

For the purpose of this investigation and simulation, we have assumed that the load draws 1MW per day. To simplify calculations, it is also assumed that the load remains constant over the year.
The calibration of the parameters for load profile is listed in Table 8:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Power</td>
<td>[MW]</td>
<td>Power drawn by the load</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 8: PowerFactory Parameters of the Load Profile

5.2 Model Validation: Performance analysis and testing
A test and performance analysis was conducted on the micro-grid model developed in PowerFactory to determine and validate the accuracy of the model. Simulation results were validated by several scenarios listed below:

- Load flow analysis via means of AC load flow, balanced, positive sequence was conducted to investigate any potential impact that the power generators might have on the network performance, in particular to obtain voltage patterns, check for possible over-load issues and demonstrate all pre-fault conditions of the model.
- Grid stability analysis to determine and identify if the grid remains stable under a sudden load change or faults in the system. This is done by analyzing the load flow graphs and looking out for any unusual behavioural changes in the measurements.

5.3 Coordination between BESS and Microgrid
The BESS is connected to the same terminal as the load. This is done to mimic a battery bank stored on the user side of the meter and also to make it easier to configure a short-circuit current simulation at the load terminal. This configuration is the method used to investigate peak power load of the system and can be triggered to monitor the BESS response to the change. Figure 16 is a simplified model of a Microgrid with a BESS and diesel generator connected to the load. The BESS is connected to the load terminal to simulate charging conditions when the diesel generator is switched on. Once the state of charge (SOC) of the BESS, set to 0.5 is reached; the diesel generator switches off and the BESS supplies power to the load. A peak power analysis was conducted and the results were analyzed.
Figure 16 BESS and Microgrid Model for simulating Peak Power
5.4 Investigating Peak Power Loads

A time analysis study into the ability of the BESS and the diesel generator to meet peak power demands of an electrical grid was conducted. The load was increased by 10% in both scenarios in order to simulate a sudden increase in demand also known as instantaneous peak power demand. The plots measured the response time taken for a standard 5MW diesel generator and a battery bank to meet the load increase.

Figure 17: Simulation results of the Diesel Generator with a load step increase of 10%
As noticed from the graphs, the response time taken for the diesel generator and battery bank is different from one another. The diesel generator takes a longer time to stabilize whereas, the battery bank is almost instantaneous in its ability to meet the sudden increase in power. This suggests that the BESS is able to meet peak load effectively and immediately. However, this scenario is only for low load current and power cases. This is due to the fact that the battery is only sized to handle a 1MW load or less. A battery bank is limited by its ampere hour capacity and response is dependent upon loads drawing capacity away from the bank at a tolerable capacity. The diesel generator will be able to meet loads larger than its rated capacity of up to 10% more. Further study into this will be required before any definitive conclusion can be made about the BESS ability to meet peak power demands.

5.5 Investigation of Transient Voltage Stability
The investigation of transient voltage stability was intended to observe how the system becomes transiently unstable and how to mitigate this problem by installing a BESS.
5.6 Dispatch Strategy of a Wind-Diesel Hybrid System with an attached BESS

The dispatch strategy proposed in this thesis has the four options of maximizing the potential of the BESS under different topology configurations and load conditions. The purpose of having these dispatch strategy analyzed is to measure the voltage stability of the grid under different control strategies [20]. This is achieved by analyzing the frequency deviations, fuel consumption, expected lifetime of the batteries, and the performance of the diesel generators. Here are the four proposed control strategies. The proposed control strategies are broken into primary and secondary control, where both are interchangeable between the BESS and generator providing the mechanism of control.

5.6.1 Control Strategy 1

This strategy represents the operation of the wind-farm plant when the primary control is provided by the diesel generator 1 and 2 with the BESS is in parallel with the system. The secondary control is provided by only the BESS.

5.6.2 Control Strategy 2

This strategy represents the operation of the wind-farm plant where the primary control is provided by the diesel generator and the BESS is in parallel. The secondary control is then provided by the diesel generator 1 with the BESS in parallel.

5.6.3 Control Strategy 3

This strategy represents the operation of the wind-farm plant when the primary control and secondary control is provided by only the BESS.

5.6.4 Control Strategy 4

This strategy represents the operation of the wind-farm plant when the primary control is provided by only the BESS. The secondary control is provided by the diesel generator and the BESS in parallel.
5.7 Control Strategy proposed methodology of testing

The first proposed control strategy test is a frequency deviation analysis on the different control strategies of the system. A frequency deviation is related to the ability of the control strategy to compensate for power fluctuations in the grid as the load varies over a period of time.

The simulation can achieve an accurate frequency deviation measurement by simulating the load over a period of 24 hours or a day; then obtaining the data of the grid frequency and analyzing the power fluctuations throughout the time period. A histogram plot of the frequency deviation for the simulated day can be produced in accordance to the respective control strategies. Finally, the data can be analyzed and a conclusion of which control strategy was the best can be determined by which strategy had the smallest frequency deviation.

The second proposed control strategy test is an estimation of the total fuel consumption (litre/kWh) for the diesel generators. This test was proposed because fuel consumption is an important part of any control strategy. The lower the fuel consumption is, the better the control strategy is.

The third proposed control strategy test is an analysis of the overall battery lifetime. Control strategy will have an effect on the lifetime of a battery as it discharges and charges the battery based upon the state of charge and how often the batteries gets used. It can be concluded that the more annual energy cycled through-out the battery bank, the shorter the lifetime of the battery can be expected. Replacing a battery bank can be an expensive process and will lower the over-all attractiveness of the proposed control strategy.

The fourth and final proposed control strategy test is to analyze the performance of the diesel generators. It is not very efficient to be running diesel generators at low or under-load conditions as this will increase the fuel consumption, high friction and slobbering problems. Consequently, over-loading a diesel generator is restricted by the Australian Standards and as stipulated, is only allowed to operate under such conditions for 1 hour in every 12 hours of operation [21].
Chapter 6

6.1 Conclusion
The lead acid battery model was successfully implemented in Simulink Matlab software and
was used to simulate the SOC and nominal voltage levels of different batteries with results
depending on the values obtained from manufacturers data-sheets. The benefit of the model is
that any user may use it to analyze the response of a battery to any load conditions required to
find the state of charge for charging and discharging conditions that the battery may operate in.

The study of a battery bank in a hybrid power system were developed and a simulation to
analyze the peak power loads, & transient voltage conditions were conducted. The findings
show that the battery bank is able to meet peak power loads for low load conditions where the
size of the battery bank is at its most effective. A feasibility analysis is recommended to be
conducted on the battery simulation to determine whether the battery bank can be used to
replace a diesel generator by meeting low load power demand.

A dispatch strategy based upon the control of the state of charge of a BESS was proposed. The
hybrid system also included a couple of diesel generators connected to a distributed generation
grid. Unfortunately, this thesis ran out of time in analyzing this last bit of research and may
require further investigation into the effectiveness of the dispatch strategy. This thesis did
however propose a methodology of conducting a dispatch strategy should someone deem to
pursue this avenue for their own thesis research in the future.

Consequently, more time would be required to improve the lead acid battery model so that it
can measure the open-circuit voltage and internal resistance over a longer period of charging
and discharging conditions. Although this may not be required as the SimScape™ model is
able to run such a simulation and obtain accurate values that can then be analyzed with
data from a manufacturers’ data-sheet. Furthermore, there is a need to build an experimental
set-up to interpolate manufacturer results for comparison purposes to further validate the
accuracy of the model.
The battery bank has come a long way in terms of development and maturity of the associated technology. A properly installed and well-maintained battery bank is capable of providing an energy capture and storage solution for distributed generation.

6.2 Future Work
This thesis has analyzed a lead acid battery model in Simulink Matlab software. There is still room for improving the model and as such a comprehensive list of potential future work is suggested in this section. The first would be to reconfigure the Simulink model to simulate different battery types. It is possible to achieve this with the current developed model, thus, following the methodology in this thesis and obtaining manufacturers data-sheet will be sufficient to conduct an analysis into different battery types.

As for the battery bank in a distributed power system model developed in this thesis; a further analysis could be conducted by analyzing a complete distributed power generation system by adding a Wind Turbine, PV & Diesel generator model along-side the Battery Bank in the PowerFactory simulation.

As explained, there wasn’t sufficient time to fully cover the dispatch strategy. Thus an investigation could be conducted into which strategy proved to be the most comprehensive. An investigative study should also include the baseline results and levelized cost of energy (COE). Any research into this would determine whether or not the BESS is actually required in distributed generation.

A feasibility study and comparison with a case study scenario could be relevant to this topic of research. For example, the Port Augusta newly proposed Solar and diesel generator power generation station [22] could be analyzed with the tools and methodology used in this thesis.
References


Appendices

Appendix A: Manufacturer Data-Sheets

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal Voltage</strong></td>
<td>12V</td>
</tr>
<tr>
<td><strong>Rated Capacity</strong></td>
<td>150AH</td>
</tr>
<tr>
<td><strong>Total Height</strong> (with terminals)</td>
<td>273mm (10.75 inches)</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>269mm (10.59 inches)</td>
</tr>
<tr>
<td><strong>Length</strong></td>
<td>327mm (12.87 inches)</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>182mm (7.17 inches)</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>Approx. 42.6kg (93.92lbs)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
<td></td>
</tr>
<tr>
<td>77°F (25°C)</td>
<td></td>
</tr>
<tr>
<td>20 hour rate (7.5A to 10.5 Volts)</td>
<td>150AH</td>
</tr>
<tr>
<td>10 hour rate (12.5A to 10.5 Volts)</td>
<td>125AH</td>
</tr>
<tr>
<td>5 hour rate (24.6A to 10.2 Volts)</td>
<td>123AH</td>
</tr>
<tr>
<td><strong>Internal Resistance</strong></td>
<td>Full charged 77°F (25°C) 2.8mΩ</td>
</tr>
<tr>
<td><strong>Capacity affected by Temperature (20 hour rate)</strong></td>
<td></td>
</tr>
<tr>
<td>77°F (25°C)</td>
<td>102%</td>
</tr>
<tr>
<td>32°F (0°C)</td>
<td>100%</td>
</tr>
<tr>
<td>5°F (-15°C)</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Self-Discharge</strong></td>
<td></td>
</tr>
<tr>
<td>77°F (25°C)</td>
<td>91%</td>
</tr>
<tr>
<td>Capacity after 3 month storage</td>
<td></td>
</tr>
<tr>
<td>Capacity after 6 month storage</td>
<td>82%</td>
</tr>
<tr>
<td>Capacity after 12 month storage</td>
<td>64%</td>
</tr>
<tr>
<td><strong>Standard Terminal</strong></td>
<td>M8</td>
</tr>
<tr>
<td><strong>Max. Discharge Current</strong></td>
<td>1500A (5s)</td>
</tr>
<tr>
<td><strong>Cranking Performance</strong></td>
<td></td>
</tr>
<tr>
<td>Cranking Amps (10 secamps to 7.2V @ 32°F (0°C))</td>
<td>1050A</td>
</tr>
<tr>
<td>Cold Cranking Amps (10 secamps to 7.2V @ 0°F (-18°C))</td>
<td>900A</td>
</tr>
<tr>
<td><strong>Reserved Capacity</strong></td>
<td>@ 25Amps 295Min</td>
</tr>
<tr>
<td>@ 75Amps 88Min</td>
<td></td>
</tr>
<tr>
<td><strong>Charging (Constant Voltage)</strong></td>
<td></td>
</tr>
<tr>
<td>Cycle Initial Charging Current 50A or Small 14.5V ~ 14.9V/77°F (25°C)</td>
<td></td>
</tr>
<tr>
<td>Float 13.6V ~ 13.8V/77°F (25°C)</td>
<td></td>
</tr>
</tbody>
</table>

Discharge characteristics 77°F (25°C)

Duration of discharge vs. Discharge current

Table 9: FullRiver 12V 150Ah
<table>
<thead>
<tr>
<th>BCI Group Size</th>
<th>Type</th>
<th>Voltage</th>
<th>Capacity (Minutes)</th>
<th>Cranking Performance</th>
<th>5 Hr Rate (AH)</th>
<th>20 Hr Rate (AH)</th>
<th>Dimensions (inches (mm))</th>
<th>Weight (Ibs (kg))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>@25 Amps</td>
<td>@75 Amps</td>
<td>CCA F @0°F</td>
<td>CA E @32°F</td>
<td>L</td>
<td>W</td>
</tr>
<tr>
<td>GC2</td>
<td>T-105</td>
<td>6</td>
<td>447</td>
<td>115</td>
<td>-</td>
<td>-</td>
<td>185</td>
<td>225</td>
</tr>
<tr>
<td>GC2</td>
<td>T-125</td>
<td>6</td>
<td>488</td>
<td>132</td>
<td>-</td>
<td>-</td>
<td>195</td>
<td>240</td>
</tr>
<tr>
<td>N/A</td>
<td>J305H</td>
<td>6</td>
<td>745</td>
<td>195</td>
<td>-</td>
<td>-</td>
<td>285</td>
<td>335</td>
</tr>
<tr>
<td>N/A</td>
<td>L16H</td>
<td>6</td>
<td>885</td>
<td>225</td>
<td>-</td>
<td>-</td>
<td>345</td>
<td>420</td>
</tr>
<tr>
<td>24</td>
<td>SCS150</td>
<td>12</td>
<td>150</td>
<td>36</td>
<td>530</td>
<td>650</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>27</td>
<td>SCS200</td>
<td>12</td>
<td>200</td>
<td>52</td>
<td>620</td>
<td>760</td>
<td>95</td>
<td>115</td>
</tr>
<tr>
<td>30H</td>
<td>SCS225</td>
<td>12</td>
<td>225</td>
<td>57</td>
<td>665</td>
<td>820</td>
<td>105</td>
<td>130</td>
</tr>
<tr>
<td>N/A</td>
<td>J185H</td>
<td>12</td>
<td>415</td>
<td>110</td>
<td>-</td>
<td>-</td>
<td>180</td>
<td>215</td>
</tr>
</tbody>
</table>

**TROJAN MARINE/RV DEEP CYCLE**

| 24             | 24SM-650| 12     | 125      | -        | 700        | 860        | -    | -    | 11 1/4 (286) | 6 3/4 (171) | 9 3/4 (248) | 43 (20) |
| 24             | 24SM-1000| 12    | 165      | -        | 825       | 1025       | -    | -    | 11 1/4 (286) | 6 3/4 (171) | 9 3/4 (248) | 49 (22) |

**TROJAN MARINE/RV STARTING**

| 24             | 24SM-850MF| 12   | 125      | -        | 700       | 860        | -    | -    | 10 3/16 (258) | 6 1/2 (165) | 9 7/16 (239) | 43 (20) |
| 24             | 24SM-1000MF| 12  | 165      | -        | 825       | 1025       | -    | -    | 10 3/16 (258) | 6 1/2 (165) | 9 7/16 (239) | 49 (22) |

**TROJAN MARINE/RV MAINTENANCE FREE LEAD**

**TROJAN MARINE/RV DUAL PURPOSE**

| 24             | 24TMS | 12     | 125      | 34      | 470        | 575        | 62   | 72   | 11 1/4 (286) | 6 3/4 (171) | 9 3/4 (248) | 41 (19) |
| 24             | 24TM  | 12     | 135      | 34      | 550        | 675        | 66   | 85   | 11 1/4 (286) | 6 3/4 (171) | 9 3/4 (248) | 44 (20) |
| 27             | 27TMS | 12     | 145      | 39      | 550        | 675        | 73   | 85   | 12 3/4 (324) | 6 3/4 (171) | 9 3/4 (248) | 48 (22) |

**TROJAN MARINE/AGM DUAL PURPOSE**

| 24             | 24-AGM | 12    | 130      | -        | 440      | 620        | 61   | 80   | 10 13/16 (259) | 6 5/8 (168) | 8 7/8 (226) | 52 (24) |
| 27             | 27-AGM | 12    | 175      | -        | 560      | 780        | 76   | 100  | 12 (305) | 6 5/8 (168) | 9 3/16 (233) | 66 (30) |
| 31             | 31-AGM | 12    | 190      | -        | 720      | 950        | 83   | 110  | 13 1/16 (208) | 6 7/8 (174) | 8 11/16 (221) | 71 (32) |
| 4D             | 4D-AGM| 12     | 325      | -        | 1110     | 1420       | 131  | 165  | 20 7/8 (530) | 8 1/4 (209) | 9 3/8 (237) | 115 (52) |
| 8D             | 8D-AGM| 12     | 460      | -        | 1450     | 1850       | 179  | 230  | 20 1/2 (521) | 10 9/16 (269) | 8 7/8 (226) | 155 (70) |
| GC2            | BV-AGM| 6      | 385      | -        | 1100     | 1400       | 154  | 200  | 10 1/4 (269) | 7 1/16 (179) | 10 5/8 (270) | 65 (29) |

**MINN KOTA BY TROJAN DEEP CYCLE • 12 VOLT**

Table 10: Trojan 12V
Appendix B: Tutorial on how to use Lead Acid Battery model in Simulink/Matlab.

The Battery Cell simulink/SimScape\textsuperscript{TM} model corresponds to the Lead Acid Battery model below.

1. Open the “custom library” function coloured in blue.
2. Double click the “ssc_lead_acid_battery.mdl” function box and select unlock boxes.
3. You are now able to edit all data as you feel pleased.
Block Parameters: Main Branch Resistance, R1

Main Branch Resistance, R1

This block implements the main branch resistance $R_1 = -R_{10} \ln(\text{DOC})$ where DOC is depth of charge and $R_{10}$ is a constant. The minimum depth of charge parameter protects the solver from the infinite gradient of $dR_1/d\text{DOC}$ that occurs as DOC goes to zero. Below the minimum depth of charge, the logarithm function is linearly extrapolated whilst matching the gradient.

View source for Main Branch Resistance, R1

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance, R10</td>
<td>1 Ohm</td>
</tr>
<tr>
<td>Minimum depth of charge</td>
<td>1e-6</td>
</tr>
</tbody>
</table>

OK  Cancel  Help  Apply

Block Parameters: Main Branch Resistance, R2

Main Branch Resistance, R2

This block implements the main branch resistance, $R_2$. $R_2 = R_{20} \exp(A_{21}(1-SOC))/(1+\exp(A_{22}/I_{star}))$

View source for Main Branch Resistance, R2

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{20}$</td>
<td>1 Ohm</td>
</tr>
<tr>
<td>$A_{21}$</td>
<td>0</td>
</tr>
<tr>
<td>$A_{22}$</td>
<td>0</td>
</tr>
<tr>
<td>Nominal battery current, $I_{star}$</td>
<td>1 A</td>
</tr>
</tbody>
</table>

OK  Cancel  Help  Apply
4. After editing the values, using manufacturers data-sheet, save the “ssc_lead_acid_battery.mdl” function block before running the simulation.

5. Double click on the “Scope” to gain output readings.
Formulas used in the algorithm for each source [9].

**Main Branch Voltage**

Equation 1 is used to calculate the open-circuit voltage of one cell. This equation used to compute the Main Branch Voltage Source (Em) in Simulink Figure 9 and ICAPS Figure 10.

\[
E_m = E_{m0} - K_E (273 + \theta)(1 - SOC)
\]  

(1)

Where:

- \(E_M\) was the open – circuit voltage (EMF) in volts
- \(E_{M0}\) was the open – circuit voltage at full charge in volts
- \(K_E\) was a constant in volts/°C
- \(\theta\) was the electrolyte temperature in °C
- \(SOC\) was battery state of charge

**Terminal Resistance**

Equation 2 calculates the resistance at the battery terminals. The calculation was computed into the “R0 block” of Simulink Figure 9 and ICAPS Figure 10.

\[
R_0 = R_{00}[1 + A_0(1 - SOC)]
\]  

(2)

Where:

- \(R_0\) was a resistance in Ohms
- \(R_{00}\) was the value of \(R0\) at \(SOC = 1\) in Ohms
- \(A_0\) was a constant
- \(SOC\) was battery state of charge

**Main Branch Resistance 1**

Equation 3 calculates the resistance in the first main branch of the battery. The calculation was performed in “R1” block of Simulink Figure 9 and ICAPS Figure 10.

\[
R_1 = -R_{10}\ln(DOC)
\]  

(3)
Where:

$R_1$ was a main branch resistance in Ohms

$R_{10}$ was a constant in Ohms

DOC was battery depth of charge

**Main Branch Capacitance 1**

Equation 4 is the capacitance (or time delay) in the main branch. The calculation was performed in “C1” block of the Simulink Figure 9 and ICAPS Figure 10.

$$C_1 = \frac{\tau_1}{R_1} \quad (4)$$

Where:

$C_1$ was a main branch capacitance in Farads

$\tau_1$ was a main branch time constant in seconds

$R_1$ was a main branch resistance in Ohms

**Main Branch Resistance 2**

Equation 5 calculates the second main branch resistance. The calculation was performed in “R2” block of Simulink Figure 9 and ICAPS Figure 10.

$$R_2 = R_{20} \frac{exp[A_{21}(1-SOC)]}{1+exp([A_{22}I_m]/I^*)} \quad (5)$$

Where:

$R_2$ was a main branch resistance in Ohms

$R_{20}$ was a constant in Ohms

$A_{21}$ was a constant

$A_{22}$ was a constant

$E_M$ was the open – circuit voltage (EMF) in volts
SOC was battery state of charge

I_M was the main branch current in Amps

I * was the a nominal battery current in Amps

**Parasitic Branch Current**

Equation 6 calculates the parasitic loss current which occurred when the battery was being charged. The calculation was performed in “Ip” block of Simulink Figure 9 and ICAPS Figure 10.

\[ I_p = V_{PN}G_{p0}\exp\left(\frac{V_{PN}/(\tau_Ps+1)}{V_{po}}\right) + A_p\left(1 - \frac{\theta}{\theta_f}\right) \]  

(6)

Where:

- \( I_p \) was the current loss in the parasitic branch
- \( V_{PN} \) was the voltage at the parasitic branch
- \( G_{p0} \) was a constant in seconds
- \( \tau_P \) was a parasitic branch time constant in seconds
- \( V_{po} \) was a constant in volts
- \( A_p \) was a constant
- \( \theta \) was electrolyte temperature in °C
- \( \theta_f \) was electrolyte freezing temperature in °C
Appendix C: ICAPS PWM & Inverter Model

ICAPS: The electrical diagrams below are ICAPS representation of the model found in PowerFactory.

Pulse Width Modulator Converter:

![Circuit Diagram of PWM converter](image)

*Figure 18: Circuit Diagram of PWM converter*

E:\ICAPS\PWM.cir Setup1
.TRAN 0.0005 3
.FOUR 1 V(2)
.OPTIONS acct
.PRINT TRAN Y1
.PRINT TRAN IY2
V1 3 0 DC=1 AC=0 PULSE 0 1 0 1u 1u 0.3 1
R1 3 0 1
V2 5 0 DC=2 AC=0 PULSE 0 1 0.5 1u 1u 0.3 1
R2 5 0 1
L1 2 1 0.15915
X1 0 5 2 SUM2 { K1=1 K2=-1 }
.SUBCKT SUM2 1 2 3 {K1=??? K2=???}
B1 3 0 V = {K1}*V(1) + {K2}*V(2)
.ENDS
R3 1 0 1
.END
PWM Inverter:

Figure 19: ICAPS Circuit Diagram of Inverter

E:\ICAPS\Inverter.cir Setup1
R1 2 0 1
R2 5 0 1
B1 1 0 V=V(2)>V(5) ? 10 : -10
R3 1 0 1
E1 3 0 0 1 1
R4 3 0 1
Vctrl 2 0 SIN 0 0.8 1 0 0 0
Vtri 5 0 PWL 0 0 0.05 1 0.15 -1 0.2 0
V4 7 0 DC=100
D1 9 7 NEWDIODE1
.MODEL NEWDIODE1 D
D2 10 7 NEWDIODE1
X1 7 9 1 SWITCH { }
.SUBCKT SWITCH 1 2 3
*Connections  Term1 Term2 Control
* The switch is OPEN WHEN V(3) = 0, It is CLOSED WHEN V(3) <> 0
* The ON RESISTANCE IS 1 / V(3)
* The OFF RESISTANCE IS 1E10
R1 1 2 1E10
G1 1 2 POLY(2) 1 2 3 0 0 0 0 1
X2 7 10 3 SWITCH { }
D3 0 9 NEWDIODE1
D4 0 10 NEWDIODE1
X3 9 0 3 SWITCH { }
X4 10 0 1 SWITCH { }
R5 9 11 10
L1 11 12 1.5915
Vtest 12 10 DC=0
.END