DOE Energy Storage Program Organization 6353

Sandia National Laboratories

Energy Storage System Model Development for Grid-Tied Renewable Applications

NC STATE UNIVERSITY

FREEDM Systems Center

Daniel Fregosi
djfregos@ncsu.edu

Advisors: Dr. Stanley Atcitty
satcitt@sandia.gov

Dr. Subhashish Bhattacharya
sbhattacharya@ncsu.edu

Introduction

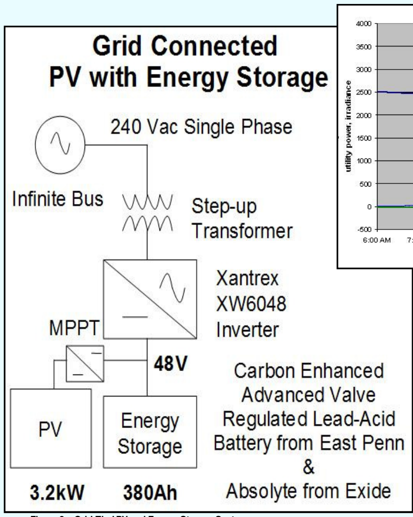

Figure 2 – Grid-Tied PV and Energy Storage System

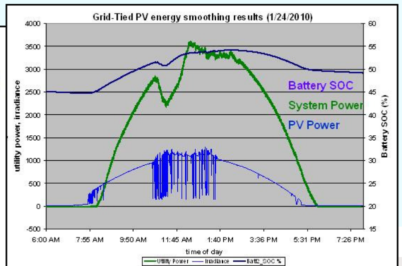

Figure 1 – Irradiance and Smoothing Algorithm Output over a Day

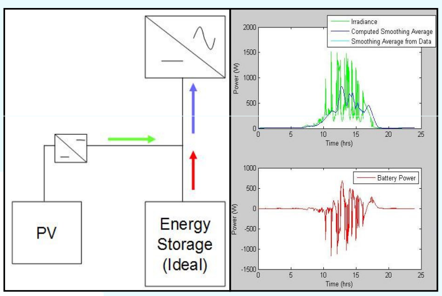

Figure 3 – Power Output for the Three Elements in the System over a Day

Background

Intermittent power which is put onto the grid must be rate limited to allow for slow reacting generators to respond to fluctuations

This is done through the use of energy storage

The Problem

Current systems control the load put onto the battery indirectly

Un-optimal charging and discharging of the battery causes a decrease in:

- **round trip efficiency**
- **battery utilization**
- **battery lifetime**

Our Plan

Model the system including a detailed electrical battery model
Verify the model matches the collected data
Design control based on battery electrochemistry knowledge
Verify improvements, first in simulation, then on actual system

Inverter Model

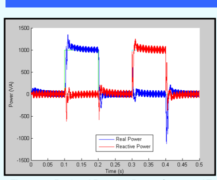

Figure 4 – Real and Reactive Power Command Tracking

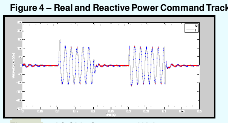

Figure 5 – AC Side Current and Voltage

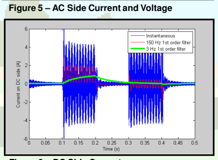

Figure 6 – DC Side Current

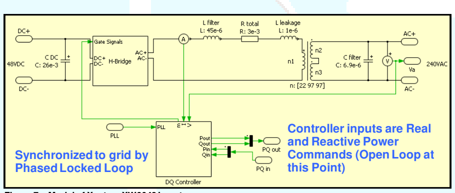

Figure 7 – Model of Xantrex XW6048 Inverter

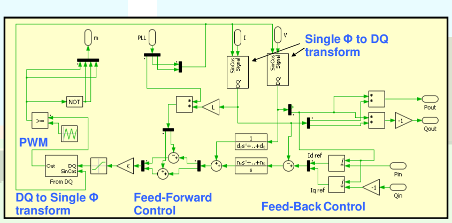

Figure 8 – Inverter Controller in Synchronous Reference Frame

Battery Model

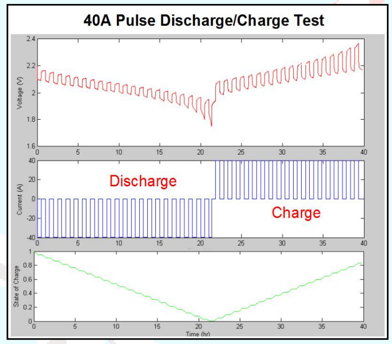

Figure 9 – Battery Voltage, Current, and State of Charge for Characterization Test

Characteristics Modeled

Open Circuit Voltage
Polarization Effect
Electric Resistance

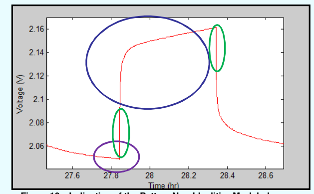

Figure 10 – Indication of the Battery Non-Idealities Modeled

Curves were fit to the equation

$$V = V_{oc} + I*R_{Series} + I*(e^{-RI*CI*t} + e^{-Rs*Cs*t})$$

Each parameter value in the equation was found as a function of state of charge and incorporated into a model

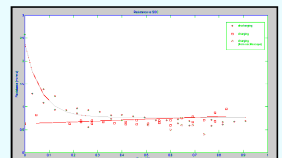

Figure 11 – Electric Resistance vs. State of Charge

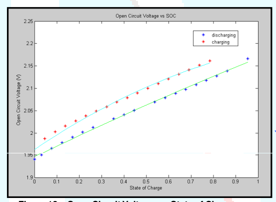

Figure 12 – Open Circuit Voltage vs. State of Charge

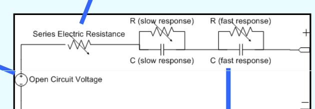

Figure 13 – Battery Model

Figure 14 – Carbon Enhanced Advanced Lead Acid Battery From East Penn (48V Module)

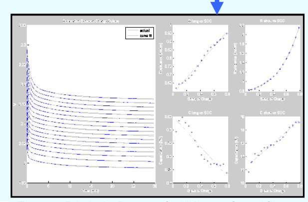

Figure 15 – Polarization Parameter Coefficients vs. State of Charge

Results

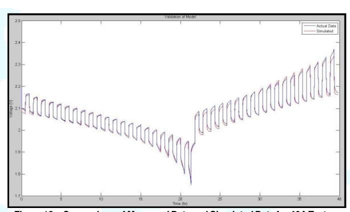

Figure 16 – Comparison of Measured Data and Simulated Data for 40A Test

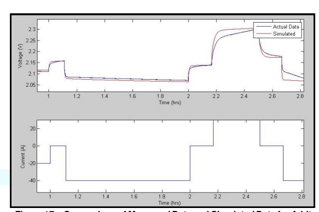

Figure 17 – Comparison of Measured Data and Simulated Data for Arbitrary Profile

$$RMS\_Error = \sqrt{\frac{\sum(Actual - Simulated)^2}{\#Samples}}$$

$$Energy\_returned = \frac{Energy\_Out}{Energy\_In}$$

Profile	RMS Error	% of 2V	Energy returned: from Data	Energy returned: from Model	% Error
40A	7.6 mV	0.38 %	91.63 %	91.41 %	0.22 %
60 A	26.0 mV	1.3 %	84.99 %	85.82 %	0.83 %
Arbitrary	12.1 mV	0.61 %	55.32 %	55.63 %	0.31 %

Figure 18 – Table Summarizing the Accuracy of the Battery Model

Future Work

Complete and verify battery model and model of entire system
Optimize System Configuration
Optimize Control of system