Modeling Improved Behavior in Stand-Alone PV Systems with Battery-Ultracapacitor Hybrid Systems

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ABSTRACT

The purpose of this study is to compare two PV-energy storage systems through simulation and measurement. In the initial case, only batteries are used for energy storage, while the comparative case uses a new battery-ultracapacitor hybrid. Simulation of the performance of the two energy storage systems is done using VisSim, with the future goal of using TRNSYS, a modular FORTRAN-based energy modeling software. A model of the ultracapacitor is being made that incorporates this frequency dependent behavior. This model is compatible with TRNSYS using which the battery-ultracapacitor hybrid system will be simulated. The testing will be performed on stand-alone PV systems and compared with simulation results. The results of the tests will enable us to directly compare measured system performance to modeled performance. The performance parameters compared are load response and peak power delivered for both the systems.

1. INTRODUCTION

The Alternate Energy Portfolio Standards require the Electric Generation suppliers in the United States to rapidly ramp up their energy portfolio with renewable energy systems like wind and solar energy which are highly intermittent. For large scale systems of wind and solar energy it is absolutely essential that the energy storage system has the capability to perfectly match the requirement. Although there exist current technologies such gas generators and batteries which can provide the fill-in power, they would have to be oversized in order to meet the fast fluctuations of the intermittent systems.[1] It has been noted that at large penetration of renewables, it is more efficient to match the fluctuations of these intermittent renewable sources with an ensemble of firm power sources than with a single source.[1] In this context ultracapacitors which have a high power density are being explored as a part of this ensemble of energy storage options for the both wind and solar energy systems. Prior studies have noted that an efficient mix would be to have fast devices (higher power densities) like ultracapacitors to match fluctuations at high frequency and low amplitude and the traditional linear ramp rate generators can be used to match the fluctuations at high amplitude and low frequency. [1, 2]

Traditionally, batteries have been used for energy storage in a small-scale stand-alone solar or a wind system. However, ultracapacitors are emerging as an excellent complement for batteries. The battery-ultracapacitor hybrid system promises better performance, due to the fact that the ultracapacitors have much higher power densities than the batteries.[3] The use of ultracapacitors as a complement to batteries has a documented increase in the battery life.[4] The ability to shift peak power delivery can also be enhanced using an ultracapacitor-battery hybrid system.[5]

2. NOMENCLATURE

C-Capacitance [F]

ESR-Equivalent Series Resistance

EPR-Charging and Discharging resistance

V_1*-Voltage drop across ESR [V]*

V_2*-Voltage drop across EPR [V]*

I_1*-Current through ESR [A]*

I_2-current through EPR [A]

I_3-current through capacitive component [A]

R_1-Resistance value of ESR [ohm]

R_2-Resistance value of EPR [ohm]

V_a-Source Voltage [V]

TMY-Typical Meteorological Year

3. ENERGY STORAGE SYSTEM MODELING

TRNSYS 16, a modular FORTRAN-based energy modeling software, has been chosen to simulate the performance of the energy storage system. However the TRNSYS software does not have built-in ultracapacitor models. Hence, we aim to develop a simulation of ultracapacitor performance for a new variety of ultracapacitor. The simulations are ultimately to be performed using insolation values from one minute intervals and for the insolation values measured in fifteen minute intervals for the same days. The required data will be gathered from the Rock Springs station in the SURFRAD Network (40.72°N 77.93°W) at the Pennsylvania State University. The results will be compared and correlations will be proposed in order to make the simulation model more suitable for future usage with the standard TMY3 data.

Many ultracapacitor electrodes are made from high surface area carbon materials. Typically the high surface areas are achieved by using subtractive techniques such as etching. For our model we have decided to use the parameters of an ultracapacitor made by SolRayo LLC, whose electrodes are made using additive techniques. The high performance electrodes for the chosen ultracapacitors are made by applying SiO_2 nanoparticles to commercially available carbon materials.

The first step of the modeling process was to develop a model that can simulate the chosen ultracapacitor's performance. The development of the model has to be in FORTRAN for it to be compatible with TRNSYS. A test model was first developed using VisSim before the same was coded in FORTRAN.

3.1 Preliminary Model

The ultracapacitor, at high frequencies, exhibits resistive behavior. However the threshold value of the frequency varies with the material used. In this study the threshold value, beyond which the ultracapacitor acts as a resistor, is taken to be 60Hz as per the suggestion of the manufacturer.

The basic model of an ultracapacitor consists of three components, Capacitance (C), an equivalent series resistance (ESR), and an equivalent parallel resistance. The ESR represents the charging and discharging resistance and the EPR represents self-discharging losses.[6] The EPR takes into account the leakage effects and affects only the long term storage performance of the ultracapacitor.[7] Kirchhoff's Current and Voltage Laws have been applied to this equivalent circuit in order to obtain its differential equation. This equation has then been solved analytically and has been used in the basic model developed in VisSim. The methodology is further described below.

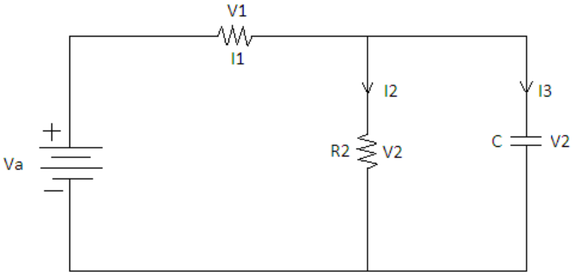

Fig. 1 Common equivalent circuit of an ultracapacitor circuit.

Kirchhoff's Voltage Law and Kirchhoff's Current Law were applied to this DC circuit shown and the following equation was obtained

$$\frac{dI_2(t)}{dt}=\frac{V_a}{CR_1R_2}-\frac{1}{C}\left[\frac{1}{R_1}+\frac{1}{R_2}\right]I_2(t) \qquad \text{(Eqn.1)}$$

This was solved analytically and the following solution was obtained,

$$I_2(t)=\frac{N\int e^{Mt}V_a+C}{e^{Mt}} \qquad \text{(Eqn.2)}$$

Where,

$$N=\frac{1}{CR_1R_2};M=\frac{1}{C}\left[\frac{1}{R_1}+\frac{1}{R_2}\right] \qquad \text{(Eqn.3)}$$

These equations have been used to model the ultracapacitor in VisSim, a dynamic simulation software. SolRayo's ultracapacitor parameters have been used as input for this model.

4. Results

The values of current and voltage for all the various sub components have been obtained. The charging cycle of the ultracapacitor has been simulated and the results are presented here.

Parameters such as size of the battery system, battery life, and cost of the system will be compared, and the benefits provided by the hybrid system will be quantified as the simulation progresses.

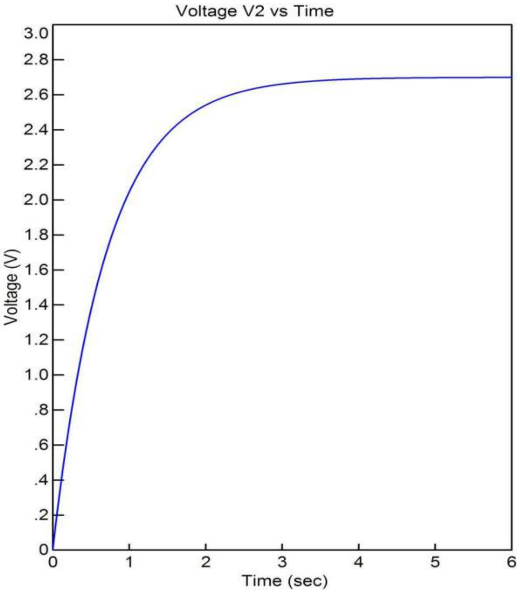

Fig.2 Voltage(V) vs Time(sec)

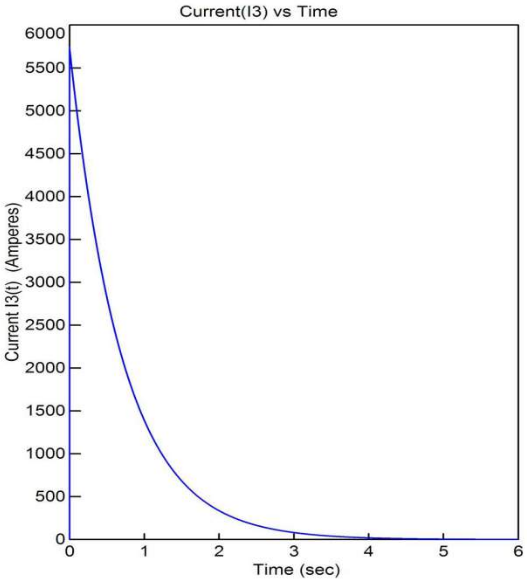

Fig. 3 Current(A) vs Time(sec)

The goal of this model was to confirm that the current vs time plot follows a quasi-exponential decay which is typically expected for a capacitor. It can be seen that the current vs time graph exhibits quasi-exponential decay for a constant source voltage hence validating the VisSim model.

4.1 Expansion of Simulation with TRNSYS

As part of future simulation runs TRNSYS will to be used to simulate the performance of battery-ultracapacitor hybrid system in conjunction with a PV system. The advantage of incorporating the ultracapacitor model into TRNSYS is largely due to the preexisting capability of TRNSYS to process weather and insolation data into a transient response system model. Currently an ultracapacitor component that is compatible with TRNSYS is being developed in FORTRAN. At present, the VisSim data is being checked against new FORTRAN algorithms. The FORTRAN component that best replicates the VisSim results will be selected and integrated with TRNSYS. The next step would be to develop a stand-alone PV system model in TRNSYS. The ultracapacitor component will be coupled with the battery and the preexisting weather data will be used to determine the transient response of the hybrid energy storage system. These results will be compared to a system containing only the battery as the energy storage system in order to quantify the benefits provided by the addition of the ultracapacitor to the system.

The final goal of this work is to quantify the benefits provided by the ultracapacitor when used in conjunction with the battery in a stand-alone PV system. The primary benefits we estimate would be better load response and higher peak power deliverance. Quantifiable benefits, if any, will be reported to SolRayo, Inc which can use the data to either improve the product or use it to promote it for applications in the PV industry. However simulation results alone will not suffice to determine these benefits. Experimental work on the ultracapacitors needs to be done in order to corroborate the simulation results. The testing will be done on a small scale stand-alone PV system during suitable months. For the corroboration to be valid, care must be taken to identify the proximity of the TMY3 data used in the simulations to the weather data observed during experimentation. Disparities in the two sets of weather data, TMY3 data and observed data, can be used to explain any disparities in the simulation and experimental results.

5. CONCLUSION

The results suggest a positive initial step in creating a TRNSYS ultracapacitor component for systems simulation. The initial verification of our ultracapacitor model through VisSim simulation is a step in the right direction. We understand that much needs to be done in order to test the quantifiable predictions with the materials from SolRayo, Inc. The immediate next step is the selection and integration of the FORTRAN model followed by the simulation of stand-alone PV system simulation with and without ultracapacitors followed by the experimental verification.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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