The Journal of CPRI,
Vol. 12, No. 3, September 2016 pp. 547-554

Modeling of hybrid ultra-capacitors for power electronic applications using PSPICE/ORCAD™

Pradeep Kumar Rao J* and Nagamani H N**

Hybrid ultra-capacitors are the integration of super capacitor and battery technologies. For performance improvement of a hybrid capacitor based system, accurate modeling is one of the requirements. Hybrid ultra-capacitor or Hybrid Capacitor (HUC) is modeled and then simulated from fundamental circuit of super capacitor with focus on leakage resistance parameter variation. Super Capacitor (SC) - MAXWELL™ 100F is simulated in its 5th order and simplified to 2nd order maintaining charge sustenance. All the simulations are performed for the first time in PSPICE/ORCAD™. The paper focuses on charging/ discharging capability of the model in time domain, such that the properties of high energy density, high power density and cycle life of the hybrid capacitors retain.

Keywords: *Supercapcitor, hybrid ultra-capacitor, modeling, simulation, PSPICE/ORCAD™.*

1.0 INTRODUCTION

Hybrid capacitors are of growing importance in the fields of traction of electric vehicle, power transmission capability and stability, Renewable energy systems [1]. It is ideal for low voltage, power- electronic integrated, intermittent power and energy load demands [2]. It avoids using super capacitors and batteries separately. Hybrid capacitors have the advantage of "No high inrush currents during light load conditions", less cost and efficient energy management with less maintenance.

Power component of any frequency can be delivered by hybrid capacitors, hence, they are under continuous stress; whereas in the integrated systems, the low frequency power component demand and the high frequency power component are supplied by battery and super capacitor respectively for dynamic load fluctuations to meet fast voltage regulation and reducing the current stress on battery [3].

Electrical equivalent circuits of super capacitor models would show identical behavior of tested super capacitors under dynamic loads. Characterization techniques of hybrid capacitors are similar to that of super capacitors [4].

Mathematical modeling of the super capacitor is explained well in simulink environment of MATLAB*™* [5]. The physical model of super capacitor i.e., the fundamental equivalent circuit with linear and nonlinear capacitance approach were explained in ORCAD*™* – CAPTURE*™* - PSPICE*™* environment of CADENCE™. Physical model of the super capacitor is not explained in the capture environment for complex equivalent circuit, to get the expected output [6-7]. Same circuit is tested for various current inputs for

*Senior Research Fellow, Capacitors Division, CPRI, Bangalore- 560080, E-mail: pradeep0265@outlook.com
**Addl. Director, Capacitors Division, Central Power Research Institute, Bangalore- 560080, E-mail: hnn@cpri.in

increased and reduced time applications and the respective results are drawn.

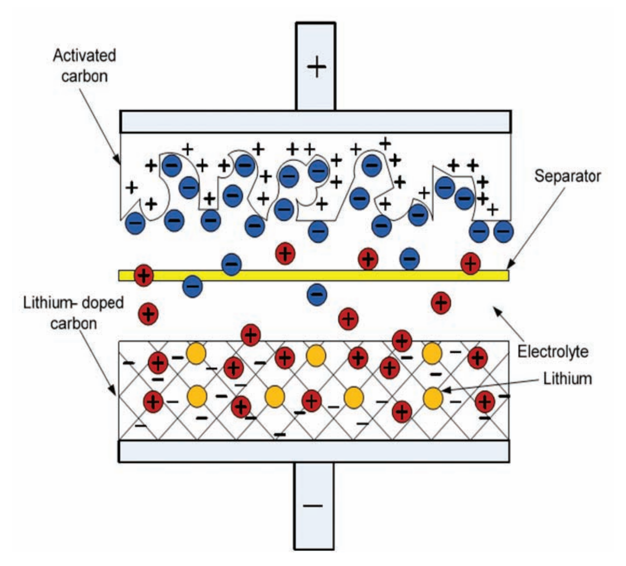

FIG. 1. LITHIUM ION HYBRID ULTRACAPACITOR (LI – ION HUC)

2.0 HYBRID ULTRACAPACITOR

Hybrid ultra-capacitors are the improved version of super capacitors, developed for the requirements of high energy and power densities. This device is an integration of battery and super capacitor [8].

From experimental studies, capacitor is built with its anode same as of the electrode terminals of super capacitor (carbon made) and the cathode is same as one of the electrode(s) of battery. Lithium ion capacitor (LiC) is a hybrid capacitor with carbon electrode as anode and lithium oxide terminal as cathode. Similarly based on requirements of high energy density and high power densities various combination of anode and cathode terminals can be selected.

Electrolyte can be aqueous, acidic, alkaline based or ionic form [8, 9]. Based on the porosity of electrode i.e., anode and cathode and depending on its surface area, electrolyte is chosen [10] such that, when the hybrid capacitor is charged, the ions in electrolyte, i.e., anions and cat-ions get deposited in anode and cathode respectively deep into micro-pore membranes based on the tailoring of ion size in the electrolyte and pore size in the electrode [11].

TABLE 1

Technical datasheet values of a 1200 F and 2400 F Lithium ion Capacitor [11]

Cap model	min/max voltage	E (Joules)	P(Watts) @ I=75A
1200F	2.2/3.8V	12	1000
2400F	2.2/3.8V	14	1000

From the technical data in the above tabular column, we can analyse the maximum and minimum capacitances offered by 1200 F and 2400 F LiC, energy and power provided in joules and watts at load current of 75 A. For more dynamic response analysis (as current profile or voltage profile), we need to analyse through electrical equivalent circuit studies.

2.1 Electrical Equivalent Circuit

Electrical equivalent circuit of the super capacitor can be designed in time domain, and frequency domain [10]. Here time domain approach is considered, electrical circuit parameters are extracted based on the voltage and current characteristics gained from simulation in PSPICE™ environment.

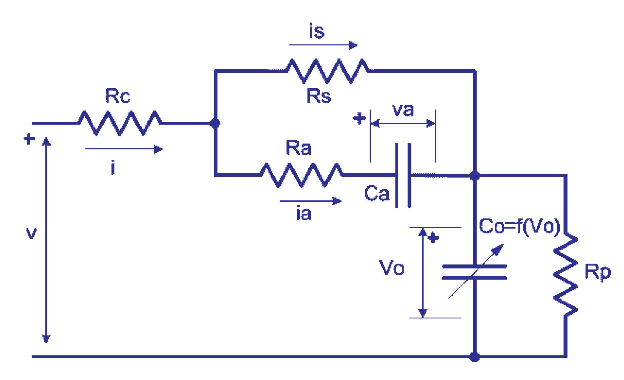

FIG. 2. EQUIVALENT CIRCUIT OF LITHIUM ION CAPACITOR[6]

In the electrical equivalent circuit shown in Figure 2; R_c corresponds to the internal series resistance, followed by the parallel combination of R_s, with series R_a and C_a. This combination represents lithium ion doped carbon layer porosity equivalence, whose value R_s goes on increasing with decrease of frequency. This branch represents electrical equivalence of Lithium ion battery where parameters represent, the leakage effect of the same. Parallel combination of R_p with C_o represents super capacitor effect, where Capacitance is chosen as voltage controlled device, as the capacitance of a super capacitor is non-linear which can be studied in depth from electrochemical impedance spectroscopy.

Super capacitor fundamental circuit as shown in Figure 3 is equally applicable to Hybrid capacitors, when temperature sensitivity is within range of -40°C to 55°C. [8, 12]

$$C = \frac{\Delta Q}{\Delta V} \quad ...(1)$$

where'C' represents the actual capacitance and Q = $\int i(t)dt$, and V = voltage applied.

$$Cp = \frac{C}{13} \quad ...(2)$$

$$R1 = \frac{\Delta V}{\Delta i} \quad ...(3)$$

R2 = depends on self-discharge, so from observations it is fixed.

$$R3 = \frac{\Delta t}{-\ln\left(\frac{V_1}{V_0}\right)c} \quad ...(4)$$

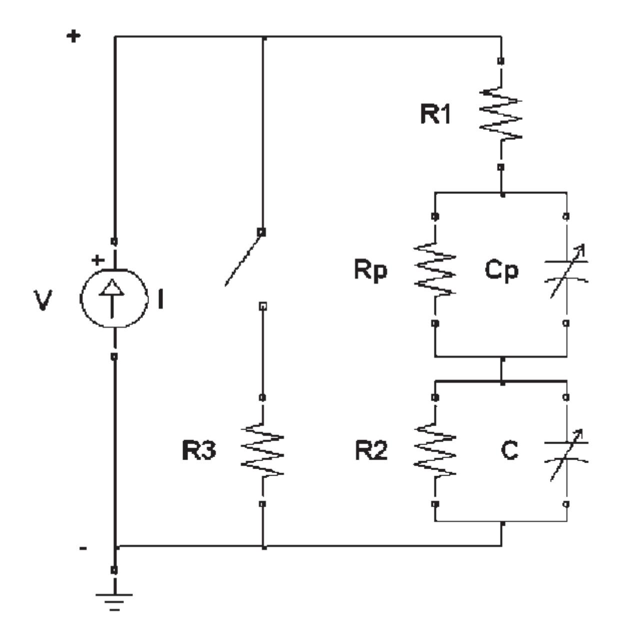

FIG. 3. PSPICE BASED FUNDAMENTAL ELECTRICAL DOUBLE LAYER CAPACITOR / HYBRID CAPACITOR CIRCUIT

3.0 PROPOSED MODEL DESIGN

Table 2 represents parameters of series combination of six 2V/3000 F HUCs.

TABLE 2

Parameters of Hybrid capacitor [8]

Sl. No	Parameter	Value
1.	Nominal voltage	2Vx6 = 12 V
2.	Capacitance	3000/6 = 500 F

$$\Delta Q = I\Delta t \quad ...(5)$$

Where ΔQ represents amount of charge stored due to current I in time Δt

Design:

An HUC can be charged almost from dead state (0.94 V) to active state (11.5 V) within very less time.

Step 1:

$\Delta Q = C\Delta V$

= 500 x (11.5–0.94) = 5280 coulombs.

A capacitor string of 500 F can store 5280 coulombs of charge.

Time needed to charge the capacitor is

$$\Delta t = \frac{\Delta Q}{I} = \frac{5280}{100} = 52.8 \approx 53 \text{ sec.}$$

So, injecting 100A for 60 sec to 500 F HUC, charges the capacitor to 12 V.

Balancing resistor = R1 = 4 mΩ or can be neglected.

Step 2:

Since capacitance of the module is chosen as C = 500F, Leakage capacitance = Cp = C/13 = 500/13 ≈ 40F.

Step 3:

Rp represents the sharp shoot of over voltage;

$$Rp = \frac{\Delta U}{\Delta I} = \frac{13.291-11.994}{|0-10|} = 13.47 \text{ m}\Omega \approx 15 \text{ m}\Omega.$$

R_2 represents the leakage resistance of hybrid capacitor, which needs to be much higher value compared to milli ohms, since milli ohmic value of resistance correspond to high leakage currents. From observations in simulation, R2 = 300 Ω, may be the best approximation.

Here the simulation is performed for different values of R2 from 10 mΩ to 10 KΩ with the increment of 100, and all the results are shown in the result.

Step 4:

R3 corresponds to self-discharge resistance,

$$R3 = \frac{\Delta t}{-\ln\left(\frac{V_1}{V_0}\right)c} = \frac{100}{-\ln\left(\frac{11.361}{11.575}\right)*500} = 10.75\ \Omega.$$

$\approx 10\ \Omega$.

4.0 RESULTS

PSPICE™ simulation model is simulated with voltage controlled switch model as shown in Figure 4, through dynamic piecewise linear current pulse generator or current source.

As the extension of Figure 5, R_2 is simulated with 300 Ω, whose simulation is visible in Figure 6.

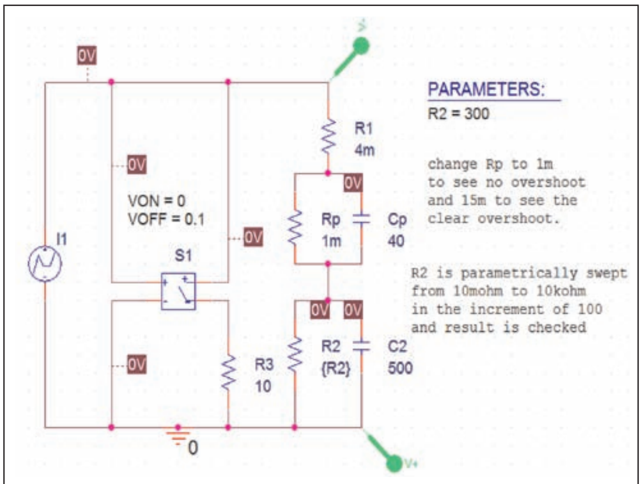

FIG. 4. PSPICE FUNDAMENTAL MODEL CIRCUIT OF HYBRID CAPACITOR MODULE (6 CAPACITORS IN SERIES) WITH LEAKAGE RESISTANCE PARAMETRIC SWEEP.

As voltage reaches maximum, it discharges through 10 ohm resistance. Simulation results of fundamental circuit for parametric sweep of leakage resistance is observed in Figure 5 and can be concluded as any leakage resistance value higher than 10 mΩ, show same dynamic response. From Figure 5, it can be inferred that except for 10 m Ω, all other values show the same type of response.

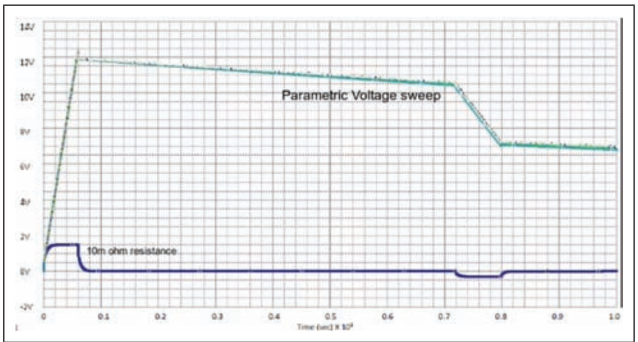

FIG. 5. SIMULATION RESULT OF FUNDAMENTAL CIRCUIT FOR R2 PARAMETRIC SWEEP.

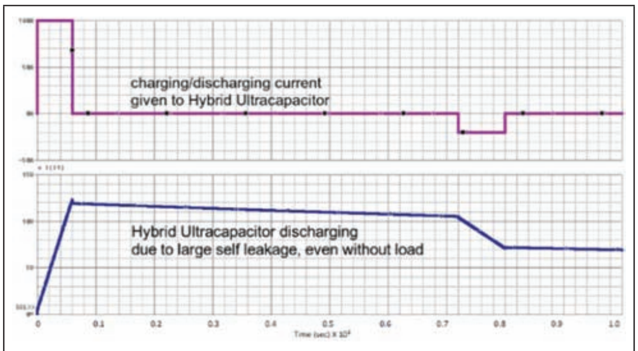

FIG. 6. SIMULATION RESULT OF FUNDAMENTAL CIRCUIT FOR VALUE OF R2 CHOSEN - 300 Ω.

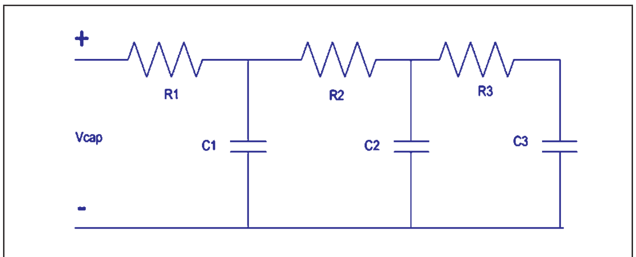

FIG. 7: 3RD ORDER RC LADDER NETWORK WITHOUT INDUCTANCE.

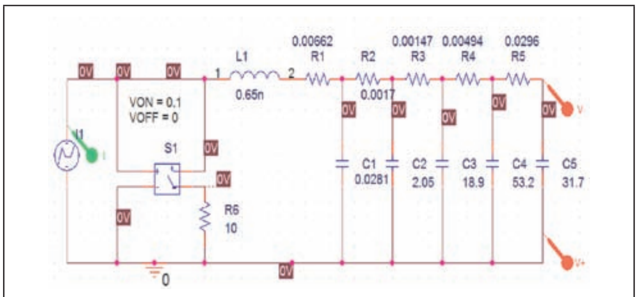

FIG. 8. 5TH ORDER LADDER EQUIVALENT CIRCUIT OF MAXWELL™ 100F IN PSPICE

Simulation of super capacitor, is not performed in the complex model for higher order models more than 3rd order in the PSPICE™ environment, which is performed here, by considering the complex RC ladder network model of the super capacitor as shown in Figure 7. MAXWELL™ 100 F super capacitor is chosen for simulation studies of the same in 5th order and then reduced to 2nd order.

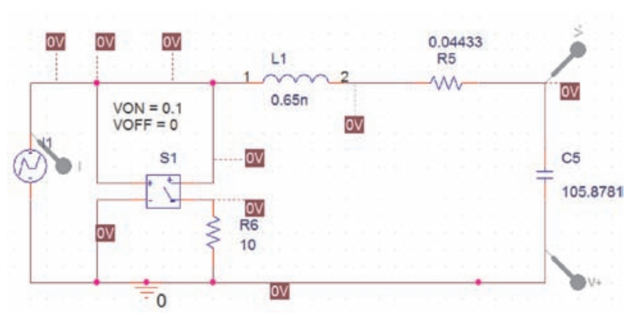

FIG. 9. REDUCED 2ND ORDER EQUIVALENT CIRCUIT OF MAXWELL™ 100F.

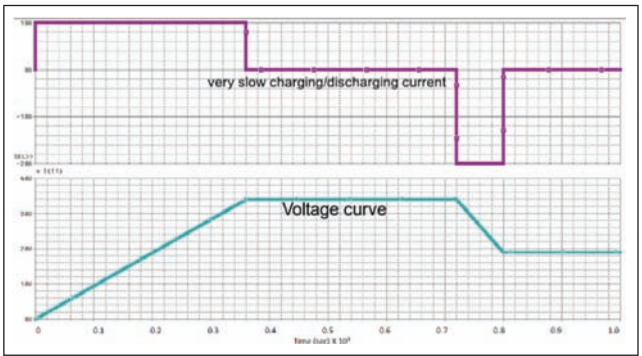

FIG. 10. PSPICE RESULT FOR FIG 8 AND FIG 9 OF CHARGING THE SUPERCAPACITOR WITH LESS CURRENT IN MORE TIME

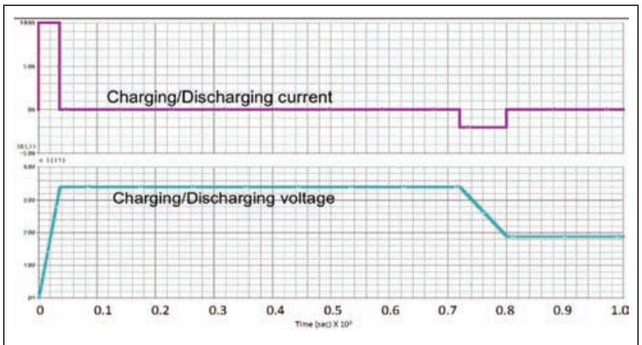

FIG. 11. PSPICE RESULT FOR FIG 8 AND FIG 9 OF CHARGING THE SUPERCAPACITOR WITH HIGH CURRENT IN LESS TIME.

PSPICE models of the 5th order MAXWELL™ 100 F super capacitor is shown in Figure (s). 8 and 9, whose response is presented in Figure 10 and 11.

Based on the parameters extracted from MAXWELL™ 34 V/100 F supercapacitor module discussed in [11], PSPICE™ model of the same is built and simulated. Model parameters can be seen in table III. 5th order super capacitor electrical equivalent circuit applicable in low voltage power electronic control of aerospace applications is simulated in Figure 8 for dynamic current profile.

TABLE 3

Model Parameters of MAXWELL™ 100F module built for 34 V supply [4, 10, and 11].

L	6.5e-8 H	C1	31.7 F
R1	0.0296 Ω	C2	53.2 F
R2	0.00494 Ω	C3	18.9 F
R3	0.00147 Ω	C4	2.05 F
R4	0.0017 Ω	C5	0.0281 F
R5	0.00662 Ω		

5.0 DISCUSSION

HUC and SC Models are designed with the objective of,designing an electrical equivalent model in simulation environment for energy storage system.Ultra capacitor model(s) can be applied to Micro grid, having Distributed Energy Resources (solar, wind etc.,) integrated with power electronic converters.

The proposed HUC models, (for details refer to table I) are designed for 6 capacitors (HUCs) connected in series, to get a module voltage and capacitance of 12 V and 500 F respectively.

Model design is based on an assumptionthat C2 = 500 F in simulation (referred to Figure 4). Modelling circuit is designed based on the mathematical formulae referred in section 3. Literature survey on the area of modelling HUC and SC indicate that, Fărcaş *et al.* [11], was not able to explain the existence of R2 clearly. In order to overcome this gap, the present work was taken up and R2 is swept for different values and results are checked in PSPICE™ (refer to Figure(s). 5 and 6). Hybrid capacitor shows the self-dischargecharacteristic between charging and discharging periods from 60 sec to 720 sec.

In order to improve the charge sustenance characteristics of the hybrid capacitor,simulation studies were repeated on super capacitor MAXWELL™ 100F. The simulation was not done with fundamental model, but with more precise RC ladder network for time domain approach [5]. PSPICE™ circuit is built for the parameters values in [4,10] and charge sustenance of circuit can be seen for same charge of different currents (refer to 10A - Figure 10 and 100 A – Figure 11).

MAXWELL™ 100 F is modelled first as 5th order circuit. Charge dump and retrieval is done with scope of charge sustenance at 10 A and 100 A. Process is repeated for reduced 2nd order circuit and it was observed that the behaviour of the model don't change. The advantages of reduced 2nd order are the reduced complexity and improved simulation time.

The results of super capacitor MAXWELL™ 100 F modelling process, will be explored for hybrid capacitor module.

6.0 CONCLUSION AND FUTURE WORK

Following are the four important observations.

1. Fundamental equivalent circuit model of hybrid capacitor using leakage resistance is an improvement over super capacitor model.
2. Modelling of super capacitor MAXWELL™ 100 F has been done for the first time using 5th order and further reduced to 2nd order equivalent circuit in ORCAD/PSPICE.
3. Further refinement of super capacitor MAXWELL™ 100 F model was done with reduced 2nd order equivalent circuit model in ORCAD / PSPICE™for the first time.
4. The proposed model for hybrid capacitor appears to be more realistic as self-leakage aspect has been addressed.

It is proposed to further improve hybrid capacitor model, for reduced leakage effect similar to super capacitor model, and effect of nonlinearities of voltage and temp will be included in next designs. Validation of the same has to be tried, with the help of Electrochemical Impedance Spectroscopy (EIS) in frequency domain.

REFERENCES

[1] J M Miller, Ultra capacitor applications, ISBN: 1849190712, Institute of Engineering and Technology, 2011.

[2] H Douglas and P Pillay, Sizing ultra-capacitors for hybrid electric vehicles, 31st IEEE annual conference of industrial electronics, pp. 37-50, May 2000

[3] M Jayalakshmi, K Balasubramanian, Simple Capacitors to Super capacitors - An Overview, International journal on electrochemical sciences, Vol.3, No.11, pp.1196-1217, Nov 2008.

[4] P Johansson, Comparison of Simulation Programs for Super capacitor Modelling : Model Creation and Verification", Master of Science Thesis, Electrical Engineering Department of Energy and Environment Division of Electric Power Engineering, Chalmers university of technology, Gothenburg, Sweden, 2008.

[5] R A Dougal, L Gao, S Liu, Ultra capacitor model with automatic order selection and capacity scaling for dynamic system simulation, Journal of power sources, No. 126,pp. 250 - 257, Elsevier, 2004.

[6] A Evans, Scott Rackey, David, "Hybrid capacitor applications, 8th international seminar on double layer capacitors and similar energy storage device. (www.evanscap.com/pdf/98SW) last accessed on 4th Oct. 2016.

[7] G Mandic, Lithium-ion ultra-capacitor energy storage integrated with a variable speed wind turbine for improved power conversion control,chapter 3 and 4, University of Wisconsin-Milwaukee, Ph.D. thesis, Dec 2012.

[8] A Banerjee, Design, Development and applications R&D on substrate-Integrated Lead-carbon Hybrid ultra-capacitors, chapter 1, Ph.D. Thesis, SSSC unit, Indian Institute of Science, June 2014.

[9] Q Gao, Optimizing carbon/ carbon super capacitors in aqueous and organic electrolytes, chap 1, Ph.D. thesis, Univ of Orleans, Poland, Oct. 2013.

[10] V A Shah, P Kundu, and R Maheshwari, Improved Method for Characterization of Ultra capacitor by Constant Current Charging, International journal of Modeling and Optimization, Vol. 2, No. 3, pp. 290-294 June 2012

[11] C Farcas, DPetreus, I Ciocan and N Palaghita, Modeling and Simulation of Super capacitors, DOI: 10.1109/ SIITME.2009.5407373, IEEE explore, 2009.

[12] A M Gee, Design and Assessment of a Battery-Super capacitor Hybrid Energy Storage System for Remote Area Wind Power Systems, chapter 2 and 3, Ph.D. thesis, University of Beth. Dept. of EEE, Aug 2012.