Supercapacitor technology and its applications: a review

Gautham Prasad G, Nidheesh Shetty, Simran Thakur, Rakshitha and Bommegowda K B
Department of Electronics and Communication Engineering
N.M.A.M Institute of Technology, Nitte, Karnataka, India
E-mail: gautham.prasadg@gmail.com, nidhesh.shetty@gmail.com, raksha.rk02@gmail.com, simranthakursimran.in@gmail.com, bgowda_kbl@nitte.edu.in

Abstract: Battery technologies are well established and widely used technology but they offer several disadvantages like weight, volume, large internal resistance, poor power density, poor transient response. On the other hand, due to advancement in the material and other technology, Supercapacitor or Ultracapacitors or Electrostatic Double Layer Capacitor (EDLC) are a most promising energy storage device. They offer a greater transient response, power density, low weight, low volume and low internal resistance which make them suitable for several applications. This paper summarizes recent research and development in the field of supercapacitor technology. This paper gives a brief insight into the design, characteristics and applications of the supercapacitor.

Keywords: Supercapacitor, capacitance, constant current, constant voltage, equivalent charge resistance, electrostatic double layer capacitance.

1. Introduction
Battery technologies are well established and widely used, with applications ranging from toys to medical implants. Some of the downsides with batteries are, lower lifecycle, less power density, higher charging time, heating problem and they are not environmentally safe. There are several alternatives available to batteries, one such device of interest is Supercapacitor (SC). The supercapacitors are special capacitors with a large capacitance, they combine properties of batteries and capacitors into a single device. The supercapacitors have significantly matured over the last few years and have exhibited potential to provide advances in the energy storage system [1]. Compared to conventional battery or capacitor, charging time of supercapacitor is very less and can discharge like a regular battery. Comparatively, these are lightweight and environmentally friendly.

2. Construction and working of supercapacitor
Conventional capacitors stores energy by moving electrons from one electrode to another, SC based on carbon materials has a higher surface area, where phenomena known as the electric double layer is used to store charges. For SC involving metal oxide or polymeric materials, pseudo-capacitance is the dominant charge storage mechanism [2][3]. Though supercapacitors and electrolytic capacitors are governed by the same capacitance equations, SC can achieve higher capacitance because of thinner dielectric and higher surface area of electrodes [4]. This also allows for power density greater than battery and energy density greater than capacitors, as shown in Figure.1 [5]. Figure. 1 shows a “Ragone plot”, it shows the performance of various energy storage devices. SC occupies space between batteries and capacitors, this presents a unique advantage that makes them indispensable for applications which require high power delivered in a short time [5][6].
SC uses a dielectric material to separate two carbon-based electrodes, which not only acts as an insulator but also has electrical properties that affect the performance of SC. In SC there is no transfer of charges, instead, charges are stored electrostatically. When a voltage is applied across the terminals, an electric field is created in the electrolyte and because of this electrolyte is polarized. This causes ions to diffuse through the dielectric to the porous electrodes of opposite charges [8]. Thus electric double layer is formed at each electrode, as a result, distance between electrodes decreases and surface area of electrode increases [6][9]. The energy storage capacity depends on the active material used in the electrolyte, the surface area of electrode and utilization rate of micro-holes in the porous electrode [10].

3. Taxonomy
Supercapacitors can be classified into 3 classes: EDLC, Pseudo-capacitors and Hybrid capacitors. Based on charge storage techniques, they can be further classified as Faradaic, Non-Faradaic and combination of both. In the Faradaic process, charges are transferred between electrode and electrolyte. In Non-Faradaic process by means of physical process charges are distributed on the surface.
4. Quantitative modelling of supercapacitors

For better understanding the working principles of SC, several models are proposed. Quantitative modelling helps to predict the performance characteristics, which in turn helps to reduce time and cost of fabrication and physical experimentation. Physical characteristics cannot be completely and precisely explained with one single model, so there are different models proposed [11]. Properly characterizing SC has recently become important because of their enormous potential as energy storage devices [12]. Electrical models can be used to describe SC behaviour in terms of voltage, temperature and frequency [7][13][14][15].

Some of the basic models are [11][12][16][17][18].
1. Electrical double layer model
2. Porous electrode model
3. Equivalent Circuit Model
4. Intelligent Model

5. Charging and discharging

General SC charging and discharging cycle begins with a constant current (CC) mode followed by constant voltage (CV) mode or with a CC mode followed by constant power mode followed by CV mode. Otherwise just a CV mode [19].

Based on SC charging and discharging at constant current, Equivalent Series Resistance (ESR) and capacitance measuring methods are devised for DC characterization [20]. Initially, SC is charged at
Constant Current (CC) till it reaches a small voltage, then it is connected to a fixed voltage DC source. Then SC is discharged at CC, until voltage drop is seen at the beginning of the discharge cycle [22][23][24]. Charging time can be increased by changing some of the parameters [25]. Figure 6 shows the profile of the discharging process. SC voltage comprises of capacitive and resistive component. Voltage due to charge and discharge is represented by the capacitive component. Voltage change due to internal resistance is given by the resistive component and internal resistance is given by ESR [21]. SC charge redistribution leads to voltage drop or boost in a relatively short term compared to self-discharge [26]. Effects of supercapacitor self-discharge for low power applications and high power application have been investigated using different models [27][28][29][30].

6. Lifetime analysis
Compared to other charge storage devices, SC has a much longer lifetime. With Non-Faradaic process, there is no chemical associated as there is no transfer of charge between electrolyte and electrode, which means it can last longer than capacitors and batteries which uses chemicals to store charges. The SC with polymer electrodes has a lesser lifetime as liquid electrolytes evaporate over time, which is a function of temperature and voltage applied. Temperature and voltage plays a vital role on a lifetime of SC [31]. In designing an energy storage system an accurate aging model [32][33] plays a critical role. In order to estimate the balance charge left in the device, precise calculation of instantaneous SC energy has to be done. In a certain scenario, SC is subjected to rapid charging/discharging cycles with constant power characteristics that is, when current increases voltage decreases and vice-versa [34][35]. Increase in current causes voltage drops and these losses escalates especially when cells are connected in series [5], due to high ESR. ESR and equivalent capacitance (EC) values changes with the device age [36][37][38]. Generally, manufacturers provide ESR and EC values with 20% tolerance [34], complicating the energy balance estimation [39].

7. Selection of supercapacitor
To replace the batteries in the system, choosing the correct values and ratings of supercapacitors is very important. Also, it is important to relate capacitance and energy in terms of watts per hour. Battery charging and discharging time is calculated based on the ampere-hour rating, an equation (1) relating ampere-hour and capacitance is given below [4].

\[
Ah = \left( \frac{V_{min} + V_{max}}{2} \right) \times \left( \frac{F}{3600} \right)
\]

Here,  
Ah = Ampere hour  
F = Farad  
V_{min} and V_{max} are terminating voltage levels
Table 1. Battery equivalent capacitance rating [4]

| Sl. No. | Battery rating (mAh) | Equivalent capacitance (Farad) |
|---------|----------------------|-------------------------------|
| 1       | 1000                 | 782                           |
| 2       | 1250                 | 978                           |
| 3       | 1500                 | 1173                          |
| 4       | 1800                 | 1408                          |
| 5       | 2100                 | 1643                          |

Stacked and rolled type supercapacitor have different effective characteristics, choosing between them is also important [40]. An ideal SC must have a high energy density, high power density, high pulse current, high capacitance and low resistance.

8. Comparative analysis of supercapacitor and other storage devices

Compared to the battery or electrolytic capacitors, SC has higher energy density and higher power density together with smaller volume and weight. SC has a long life cycle compared to batteries, up to 500000 times [21]. It can be said that battery and SC are complementary because batteries are limited in the power levels they can support but have high energy to weight ratio, whereas SC can support various power levels but has lower energy to weight ratio [41]. Modern applications are high power rated, this has led to the manufacturing of batteries with high power which in turn requires to sacrifice energy density and life cycle. Similarly with the capacitors, as they now suffer from low energy density and higher self-discharge [42][43]. Compared to individual SC and battery, hybrid energy storage systems can achieve better energy and power performances [44][45]. There have been several hybrid models proposed [46][47][48] which show superiority over battery-only systems. Battery-supercapacitor, fuel cell-supercapacitor hybrid models are some examples [49][50].

Table 2. Comparison between supercapacitor, electrolytic capacitor and battery performance [13]

| Storage device characteristics | Supercapacitor | Capacitor | Battery |
|-------------------------------|---------------|-----------|---------|
| Charging time                 | 1 – 30 s      | 10^7 < t < 10^8 s | 1 < t < 5 h |
| Discharging time              | 1 – 30 s      | 10^7 < t < 10^8 s | T > 0.3 h |
| Energy density (Wh/kg)        | 1 – 10        | < 0.1     | 10 – 100 |
| Life time (Cycle number)      | 10^8          | 10^7      | 1000    |
| Power density (W/kg)          | 10,000        | > 1,000,000 | < 1000 |
| Charge / discharge efficiency | 0.85 – 0.98   | > 0.95    | 0.7 – 0.85 |

9. Advantages and future scopes

Batteries are dangerous when mistreated, overheating may cause batteries to explode. SC does not overheat because of low internal resistance. The lifecycle of batteries are low, comparatively, SC has a lifetime of virtual infinity. This makes these devices useful where it is subjected to frequent charging and discharging cycles [4]. Shorting terminals of fully charged SC will cause it to discharge quickly, which may result in electrical arching, which might damage the device.

Some of the features of supercapacitors are [51]:

i) Low ESR.
ii) Low leakage current.
iii) Higher life cycle.
iv) A wide range of operating temperature.
v) Higher useable capacity.

Some of the fields where supercapacitors can be used are:

1. In transmission lines [52].
2. SC UPS: For critical loads which need ride-through of few second, SC system without any batteries are useful [53].
3. Hybrid SC-Battery UPS: SC and battery can complement each other in their short-coming which would reduce battery cycling, in turn, increasing battery life [54].
4. System frequency and stability control [54][55].
5. Microgrid and micro-generation: SC can be used as an energy storage device in a micro source system connected to microgrid [56].
6. SCs are suited as an energy storage system for hardening sensitive equipment against voltage sag [57].
7. In a wind turbine system [58]: SC can provide a simple, highly reliable solution.
8. In telecommunication, to achieve highly reliable operation, usually, they are supported by “hot standby system” like battery backup, parallel type UPS and redundant DC-DC converter. There is some power consumption in the standby unit. It becomes a serious problem because power saving is an important issue. So they require a cold standby device like diesel generator set, fuel cell etc. But their response time is large. The solution is to use SC which operates in a shorter time as soon as an interrupt occurs in a system.
9. Cold starting of the diesel-fueled engine [59][52], diesel-fueled engines are more difficult to start at a temperature up to -40°C. Lead acid batteries are used in engine cranking. At low-temperature resistance offered by a battery is high which affect the high current discharge of a battery which is necessary in the situation. Again, battery ages, the internal resistance further increases and current discharge capability further reduces. SC bank can be used with battery to supply necessary cranking current to cranking motor.
10. Hybrid electric vehicle [59][60] use battery alone system to drive the vehicle through inverter and motor. If along with battery which is rich in energy density [44], SC which is rich in power density is used together, the transient requirement i.e., a pulse of current during acceleration is supplied by SC and during deceleration or breaking the energy will be returned back to the SC. An appreciable amount of energy used during acceleration will be regained.

10. Conclusion
In this paper, some of the characteristics of the supercapacitors have been discussed which will be helpful to select supercapacitor and design energy storage system using it. With high power density, short charging time, large discharging time, long life and environmentally friendly properties supercapacitor may be chosen as an alternative for battery or other energy storage devices.

References

[1] Chukwuka C, Folly K. A, “Batteries and Super-capacitors”, IEEE PES PowerAfrica, pp. 1 – 6, 2012.
[2] Armutlulu, J. K. Kim, M. Kim, S. A. Bidstrup Allen, M. G. Allen, “Nickel-oxide-based supercapacitors with high aspect ratio concentric cylindrical electrodes”, Transducers &Eurosensors, pp. 1480 – 1483, 2013.
[3] C. D. Lokhande, D. P. Dubal, Oh-Shim Joo, “Metal oxide thin film based supercapacitors”, Current applied physics, Vol.11, pp. 255 - 270, 2011.
[4] J. Manikandan, R. MohanaPriya, S. Pavithra, D. Sarathkumar, “Rapid Smart Phone Charging Using SuperCapacitor”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 4, pp. 2175 - 2180, 2015.
[5] Ionuț Ciocan, Cristian Fărcăș, Alin Grama, Adrian Tīlbure, “An Improved Method for the Electrical Parameters Identification of a Simplified Pspice Supercapacitor Model”, IEEE SIITME, pp. 171 - 174, 2016
[6] R. Kotz, M. Carlen, “Principles and applications of electrochemical capacitors”, Electrochimica Acta, Vol. 45, pp. 2483 - 2498, 2000.
[7] Marin S. Halper, James C. Ellenbogen, “Supercapacitors: A Brief Overview”, 2006.

[8] Z. Li, C. Jie, “An impedance-based approach to predict the state-of-charge for carbon-based supercapacitors”, Microelectronic Engineering, Vol. 85, pp. 1549 - 1554, 2008

[9] Andrew Burke, “Ultracapacitors: why, how, and where is the technology”, Journal of Power Sources, Vol. 91, pp. 37 – 50, 2000.

[10] F. Belhachemi, S. Rael, B. Davat, “A physical based model of power electric double-layer supercapacitors”, Industrial Application Conference, Vol. 5, pp. 3069 - 3076, 2000.

[11] Wang Kai, Ren Baosen, Li Liwei, Li Yuhao, Zhang Hongwei, Sui Zongqiang, “A review of Modeling Research on Supercapacitor”, Chinese Automation Congress (CAC), pp. 5998 - 6001, 2017.

[12] Paolo Bondavalli, Gregory Pognon, “Graphene-based supercapacitors fabricated using a new dynamic spray-gun deposition technique”, IEEE International Conference on Nanotechnology, pp. 564 – 567, 2015.

[13] F. Rafik, H. Gualous, R. Gallay, A. Crausaz, A. Berthon, “Frequency, thermal and voltage supercapacitor characterization and modelling”, Journal of Power Sources, Vol. 165, pp. 928 - 934, 2007.

[14] Hamid Gualous, Hasna Louahlia, Roland Gallay, “Supercapacitor Characterization and Thermal Modelling With Reversible And Irrevers Heat Effect”, IEEE transactions on power electronics, Vol. 26, pp. 3402 – 3409, 2011.

[15] Hengzhao Yang, Ying Zhang, “Evaluation of Supercapacitor Models for Wireless Sensor Network Applications”, International Conference on Signal Processing and Communication Systems (ICSPCS), pp. 1 – 6, 2011.

[16] Elena Danila, Dorin Dumitru Lucache, Gheorghe Living, “Models and modelling the supercapacitors for a defined application”, Annals of the University of Craiova Electrical Engg, Vol. 35, pp. 200 - 205, 2011.

[17] Lucia Gauchia, Sandra Castaño, Javier Sanz, “New approach to supercapacitor testing and dynamic modelling”, IEEE Vehicle Power and Propulsion Conference, pp. 1 – 5, 2010.

[18] M. Nikkhoo, E. Farjah, T. Ghanbari “A simple method for parameters identification of three branches model of supercapacitors”, Iranian Conference on Electrical Engineering (ICEE), pp. 1586 – 1590, 2016.

[19] Cheng-Chou Li, Ton-Churo Huang, Yin-Guang Leu, Ke-Chin Huang, Chin-Ming Hong, Yi-Chuan Lu, “A Stand Alone Super Capacitor Charging System Using A Feed Forward Boost Converter”, ICSSE, pp. 65 – 69, 2011.
[20] Hamid Gualous, Hicham Chaoui, Roland Gallay, “Supercapacitor Calendar Aging for Telecommunication Applications”, IEEE INTELEC, pp. 1 - 5, 2016.

[21] N. S. Zhai, Y. Y. Yao, D. L. Zhang, “Design and Optimization for a Supercapacitor Application System”, Int. Conference on Power System Technology, pp. 1 - 4, 2006.

[22] Braham Lawas Lawu, Syifaul Fuada, Surya Ramadhan, Achmad Fajar Sabana, Arif Sasongko, “Charging Supercapacitor Mechanism based-on Bidirectional DC-DC Converter for Electric ATV Motor Application”, International Symposium on Electronics and Smart Devices, pp. 129 – 132, 2017.

[23] George Kraev, Nikolay Hinov, Dimitar Arnaudov, Nikolay Rangelov, Bogdan Gilev, “Serial ZVS DC-DC Converter for Supercapacitor Charging”, International Symposium on Electrical Apparatus and Technologies, pp. 1 – 4, 2016.

[24] K. Bellache, M. B. Camara, B. Dakyo, “Characterization of Supercapacitor based on using conditions impacts evaluation on cell resistance and capacitance”, Annual Conference of the IEEE Industrial Electronics Society, pp. 2004 – 2009, 2016.

[25] Adekunlé A. Salami, Ayité S. A. Ajavon, Koffi. A. Dotche, Koffi Sa-Bedja, “Investigating the Charging Time of Supercapacitors Using Stern’s Model”, IEEE PES- IAS Power Africa, pp. 105 – 108, 2017.

[26] Hengzhao Yang, “Analysis of Supercapacitor Charge Redistribution through Constant Power Experiments”, IEEE Power and Energy Society General Meeting, pp. 1 – 5, 2017.

[27] T. Zhu, Z. Zhong, Y. Gu, T. He, and Z.-L. Zhang, “Leakage-aware energy synchronization for wireless sensor networks”, 7th International Conference on Mobile Systems, Applications, and Services, pp. 319 – 332, 2009.

[28] Y. Zhang, H. Yang, “Modelling and characterisation of supercapacitors for wireless sensor network applications”, Journal of Power Sources, Vol. 196, pp. 4128 - 4135, 2011.

[29] H. Yang, Y. Zhang, “Self-discharge analysis and characterization of supercapacitors for environmentally powered wireless sensor network applications”, Journal of Power Sources, Vol.196, pp. 8866 - 8873, 2011.

[30] N. Bertrand, O Briat, J-M. Vinassa, E-H El Brouji, “Influence of relaxation process on supercapacitor time response”, European Conference on Power Electronics and Applications, pp. 1 – 8, 2009.

[31] Rajib Sarkar Rajan, Md. Moshiur Rahman, “Lifetime Analysis of Super Capacitor for Many Power Electronics Applications”, Journal of Electrical and Electronics Engineering, Vol. 9, pp. 55 - 58, 2014.

[32] Thibaut Kovaltchouk, Bernard Multon, Hamid Ben Ahmed, Judicael Aubry and Pascal Venet, “Enhanced Aging Model for Supercapacitors taking into account Power Cycling:
Application to the Sizing of an Energy Storage System in a Direct Wave Energy Converter”, IEEE Transactions on Industry Applications, Vol. 51, pp. 2405 – 2414, 2015.

[33] K. Bellache, M.B. Camara, B. Dakyo, “Multi-physical characterization of supercapacitor”, International Conference on Ecological Vehicles and Renewable Energies, pp. 1 – 5, 2017.

[34] M. Mellincovsky et al., “Performance and limitations of a constant power fed supercapacitor”, IEEE Transactions on Energy Conversion, Vol. 29, pp. 445 - 452, 2014.

[35] D. Iannuzzi and P. Tricoli, “Speed-based state-of-charge tracking control for metro trains with onboardsupercapacitors”, IEEE Transactions on Power Electronics, Vol. 27, pp. 2129 - 2140, 2012.

[36] NassimRizoug, Patrick Bartholomeus, Philippe Le Moigne, “Study of the ageing process of a supercapacitor module using the direct method of characterization”, IEEE Transaction on Energy Conversion, Vol. 27, pp. 220 - 228, 2012.

[37] ThibautKovaltchouk, Bernard Multon, Hamid Ben Ahmed, JudicaëlAubry, Pascal Venet, “Enhanced aging model for supercapacitors taking into account power cycling: Application to the sizing of an energy storage system in a direct wave energy converter”, IEEE Transactions on Industry Applications, Vol. 51, pp. 2405-2414, 2015.

[38] N. Reichbach, M. Mellincovsky, M. M. Peretz, A. Kuperman, “Long-term wide-temperature supercapacitorRagone plot based on manufacturer datasheet”, IEEE Transactions on Energy Conversion, Vol. 31, pp. 404 – 406, 2016.

[39] Noam Reichbach, AlonKuperman, “Recursive-Least-Squares-Based Real-Time Estimation Of Supercapacitor Parameters”, IEEE transactions on energy conversion, Vol. 31, pp. 810 - 812, 2016.

[40] P. B. Karandikar, Abhay Kumar Pandey, AyushNegi, Santosh Kumar, “Comparative Study of Rolled and Stacked Type Aqueous Supercapacitor”, IEEE Global Humanitarian Technology Conference: South Asia Satellite (GHTC-SAS), pp. 260 – 263, 2013.

[41] C. M. Krishna, “Managing Battery and Supercapacitor Resources For Real-Time Sporadic Workloads”, IEEE Embedded Systems Letters, Vol. 3, pp. 32 - 36 2011.

[42] John R. Miller, “Introduction to electrochemical capacitor technology”, IEEE Electrical Insulation Magazine, Vol. 26, pp. 40 – 47, 2010.

[43] Martin Mellincovsky, AlonKuperman, ChaimLerman, IlanAharon, Noam Reichbach, Gal Geula, Ronen Nakash, “Performance assessment of a power loaded supercapacitor based on manufacturer data”, Energy Conversion and Management, Vol. 76, pp. 137 – 144, 2013.

[44] Shuai Lu, Keith A. corzine, Mehdi Ferdowsi, “A new battery/ultra capacitor energy
storage system design and its motor drive integration for hybrid electric vehicles”, IEEE transaction on vehicular technology, Vol. 56, pp. 1516 – 1523, 2007.

[45] S. D. G. Jayasinghe, D. M. Vilathgamuwa, U. K. Madawala, “A New Method of Interfacing Battery/Supercapacitor Energy Storage Systems for Distributed Energy Sources”, Conference Proceedings IPEC, pp. 1211 – 1216, 2010.

[46] Alon Kuperman, Ilan Aharon, “Battery-ultracapacitor hybrids for pulsed current loads: A review”, Renewable and Sustainable Energy Reviews, Vol. 15, pp. 981-992, 2011.

[47] Lakshimikant M. Bopche, Ankush A. Deosant, Muneeb Ahmad, “Combination of Parallel Connected Supercapacitor& Battery for Enhancing Battery Life”, International Conference on Automatic Control and Dynamic Optimization Techniques, pp. 77 – 82, 2016.

[48] Yu Zhang, Zhenhua Jiang, Xunwei Yu, “Control Strategies for Battery/Supercapacitor Hybrid Energy Storage Systems”, IEEE Energy 2030 Conference, pp. 1 – 6, 2008.

[49] Giovanni Dotelli, Roberto Ferrero, Paola Gallo Stampino, “Supercapacitor Sizing for Fast Power Dips in a Hybrid Supercapacitor—PEM Fuel Cell System”, IEEE Transactions on Instrumentation and Measurement, Vol. 65, pp. 2196 – 2203, 2016.

[50] Andrew Burke, “The Present and Projected Performance and Cost of Double-layer and PseudocapacitiveUltracapacitors for Hybrid Vehicle Applications”, IEEE Vehicle Power and Propulsion Conference, pp. 356 – 366, 2005.

[51] A. J. Calleja, A. Torres, J. Garcia, M. Rico Secades, J. Ribas, J Ángel Martínez, “Evaluation of Power LEDs Drivers with Supercapacitors and Digital Control”, IEEE Industry Applications Annual Meeting, pp. 1129 – 1134, 2007.

[52] V. A. Shah, Jivanadhar A. Joshi, Ranjan Maheshwari, Ranjit Roy, “Review of Ultracapacitor Technology and its Applications”, Fifteenth National Power Systems Conference IIT Bombay, pp. 142 – 147, 2008.

[53] A. K. Saonerkar, A. Thakre, A. Podey, A. Chimote, P. Kado, P. Kadu, R. Satpute, “Single Phase Residential Multilevel Inverter Using Supercapacitor”, International Conference on Inventive Computation Technologies, Vol. 3, pp. 1 – 4, 2016.

[54] Y. R. L. Jayawickrama, S. Rajakaruna, “Ultracapacitor Based Ridethrough System for A De Load”, International Conference on Power System Technology, Vol.l, pp. 232 – 237, 2004.

[55] Jayathu Fernando, Nihal Kularatna, Howell Round, Sadhana Talele, “Implementation of the supercapacitor-assisted surge absorber (SCASA) technique in a practical surge protector”, Annual Conference of the IEEE Industrial Electronics Society, pp. 5191 – 5195, 2014.
[56] P.J. Binduhewa, A.C. Renfrew, M. Barnes, “Ultracapacitor Energy Storage for MicroGrid Micro-generation”, IET Conference on Power Electronics, Machines and Drives, pp. 270 – 274, 2008.

[57] Maxwell Technologies, “Voltage sags; a little energy storage can go a long way”, White paper- Maxwell Technologies, www.maxwell.com.

[58] Adrian Schneuwly, “Ultracapacitors improve reliability for wind turbine pitch systems”, White paper-Maxwell Technologies, www.maxwell.com.

[59] S. Pay, Y. Baghzouz, “Effectiveness of Battery-Supercapacitor Combination in Electric Vehicles”, IEEE Bologna Power Tech Conference Proceedings, Vol. 3, pp. 1 – 6, 2003.

[60] Andrew F. Burke, “Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles”, Proceedings of the IEEE, Vol. 95, pp. 806 – 820, 2007.