 doi:10.20944/preprints201810.0135.v1

A Multi-Stage Approach to Hybrid Lead Acid Battery and Supercapacitor System for Transport Vehicles

Mpho J Lencwe
Dept. Electrical Engineering, Tshwane University of Technology, Pretoria, South Africa
mpholencwe@gmail.com

Shyama P Chowdhury
Dept. Electrical Engineering, Tshwane University of Technology, Pretoria, South Africa
Spchowdhury2010@gmail.com

Thomas O Olwal
Dept. Electrical Engineering, Tshwane University of Technology, Pretoria, South Africa
OlwalTO@tut.ac.za

Abstract

Lead Acid Batteries (LABs) are used for starting, lighting, igniting, air conditioning systems and supplying power to electric engines in Transport Vehicles (TVs). However, the application of LABs for TVs has faced a number of market challenges mounted by the upcoming high energy density and long lifespan batteries such as Lithium Ion. LABs on the other hand are low cost. The key research question is, how can the lifespan of LABs used in automotive industries be increased, while still ensuring a low cost solution? Thus, integrating LABs with the Supercapacitor is likely to outperform the competing alternative batteries for TVs.

This paper proposes a multiple stage approach to hybrid Lead Acid Battery and Supercapacitor system for TVs that is capable of maintaining the battery State-of-Charge (SOC) to statistically high limits ranging between 90% and 95%. This SOC target will likely ensure that the lifespan of the hybrid battery system can be elongated (extended) more than its competitors. In this study, the multiple stage approach of concatenated converters has been designed in order to satisfy all energy storage requirements for different characteristics of LAB and Supercapacitor.

The designed hybrid system has been simulated using Matlab/Simulink. The simulated results show that high transient currents from the DC Bus of LAB caused by the regenerative braking or deceleration of the TVs reduces the battery lifespan and induce mechanical stress. Supercapacitor reduces the stress on the LAB by absorbing high transient currents. This, in turn keeps the LABs' SOC between 90-95% and the voltage at 12V. As indicated by the simulated results, the hybrid battery SOC is maintained at 90-93% and the terminal voltage is approximately 12V.

Keywords: Lead Acid Battery, Supercapacitor, DC/DC Converter, State-of-Charge

1. Introduction

Many applications have seen the wide use of Lead Acid Batteries (LABs) and Supercapacitors in recent years. Supercapacitors are the workhorse in many applications in the automotive sector, due to their ability to last longer, absorb/provide high currents, and high efficiency. As compared to LABs, the Supercapacitors have a common characteristics of having low cost, robustness amongst other factors. Batteries alone are unable to provide the required energy for future vehicles (i.e. Hybrid Vehicles, Electric Vehicles and Plugged-In Hybrid Electric Vehicles) [1], [2], [3]-[4].

Hybrid electric vehicles (HEVs) are heavily introduced to the market due to their low carbon emission and flexibility. These vehicles demand high energy storage devices for their operation. Therefore batteries alone cannot satisfy HEVs' demands. LABs are used for starting, lighting and igniting as well as air conditioning systems. Above and beyond these functions, LABs are responsible for supplying power to electric engines. Presently, the core technical challenges encountered by automotive industries are battery lifespan. The function of the supercapacitor is to permit the battery to handle the normal energy requirements, whereas the supercapacitor handles the high power requirements. Furthermore, supercapacitor leads to reduced CO_2 emission, better fuel consumption and advanced electrical drive capabilities. With supercapacitors, recapturing and re-uses of power in regenerative braking is possible [5]. Energy management control is the most important part in Hybrid Energy Storage Systems (HESS) for TVs.

Therefore this paper proposes a multiple stage LAB and Supercapacitor hybrid system based on two DC/DC converters for TVs. This is done by using simple PID control strategy on the converter to keep the batteries SOC within limits. The PID control ensures that the batteries' output voltage and the reference voltage do not exceed 2% of the reference voltage. The battery SOC is kept within 90-93% and the voltage at 12V, as shown in figure 10. LABs are prone to last longer if their SOC is kept above 50% and their terminal voltage does not go below 10V. This ensures that the battery is not deeply discharged, which means below 50% SOC and, which will reduce its lifespan significantly. The supercapacitor assists in absorbing high current from the DC bus of the TV. Therefore the dynamic control of keeping LABs state-of-charge within limits is achieved in this paper and terminal voltage is kept constantly through the duration of the simulation.

This paper is organised as follows: Section 2 describes the related works, section 3 outlines the methodology used, Section 4 presents the results and discussions and Section 5 concludes the paper.

2. Related Work

Although the hybridization of Supercapacitor and LAB is achieved in [4], the percentage difference between the Bus Voltage and the LABs is more than 5%, which remains a concern, in terms of efficiency. Deu *et al*. [5] proposed a hybrid scheme of LAB and Supercapacitor; however, the study did not indicate a clear methodology for hybridization of LAB and Supercapacitor. In [6] and [7], a battery/supercapacitor hybrid is developed. In this design, the supercapacitor's function is to provide extra energy required to the EV load when the battery fails to deliver. The design is due to battery losing their performance over a prolonged period at peak demand operation. It is further emphasized that it is of paramount importance to employ decision based control strategies of deciding when the electrochemical cells should be charged/discharged and how. However, the study focused on understanding the phenomenon of designing the battery-supercapacitor and driving cycle in European countries. Several topologies are used for the hybridization of LABs and Supercapacitors. Sreedhar *et al.* [8] compared the different converter topologies for LAB-Supercapacitor hybrid. Simulation claims that battery peak currents are reduced and a 40% increase in vehicle range is archived. The driving cycle (route) used to test the hybrid power system that is considered here, is in the United States of America (USA), thus no other driving patterns where considered. A charge acceptance and discharged capability test is conducted for LAB coupled with supercapacitor [9]. The study flaws involve direct coupling of LAB with supercapacitor without any DC/DC converter buffer. Due to differences in characteristics of LABs and Supercapacitors, these electrochemical storage systems cannot be directly coupled to assess their performance. Two elements of energy management strategies are compared, which include; optimisation-based and rule-based strategy. The significance in both strategies is that the difference in current between the battery and supercapacitor is within ±5% [10]. In [11], hybridization of LAB and Supercapacitor is investigated without electronic interface between the two energy storage devices. The aim was to deliver high peak current from the Supercapacitor without affecting the LAB lifespan. However, the study did not indicate how good the agreement between the outputs of LAB and Supercapacitor are, and did not consider regenerative braking energy.

3. Methodology

The possibility of hybridizing lead acid battery with supercapacitor have been widely studied in [12], the hybridized system is said to provide huge energy capacity in small volume and enhances cold cranking capability in TVs. Although supercapacitors have high power density compared to LABs, they provide transient power during cold cranking at low temperatures. Currently LABs are popular, however at low temperatures; cold cranking is compromised in TVs at low SOC (i.e. below 50%). Battery and Supercapacitor models which are studied are based on simscape power system toolbox in Matlab/Simulink. The use of simscape simulation toolbox modeling for power systems design technology, is suited for evaluating the performance of energy storage systems for transport vehicles [13],[14]-[15]. The approach is to design using a battery with parameters that are commercially available and study its behavior during the simulation. The developed architecture of LAB and Supercapacitor hybrid is simulated using Matlab/Simulink. The topology used consists of two DC/DC Boost converters for LAB and Buck-Boost for Supercapacitor. The buck-boost converter for the supercapacitor operate as a bi-directional power flow system. This allows the supercapacitor to accept current

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 October 2018 doi:10.20944/preprints201810.0135.v1

for both regenerative braking energy and powering the motor. The selected LAB has parameters indicated in Table I. The LABs parameters are obtained from the commercially available Valve Regulated Lead Acid Battery (VRLAB) used in the transport vehicles daily. The operating temperature is assumed to be at room temperature as indicated. The Supercapacitor's function is to absorb or provide transients current during operation.

TABLE I Energy Storage Device Parameters.

Lead Acid Battery	**Supercapacitor**
Output voltage = 12.2733V	Rated Voltage = 12V
Capacity = 75Ah	Rated Capacitance = 500 F
Initial SOC = 100%	Number of series capacitance = 6
Temperature = 25°C	Initial Voltage = 16V
	Temperature = 25°C

The supercapacitor relieves the LAB from inrush current, which can shorten the batteries' lifespan significantly. The model developed in Matlab/Simulink is represented by a flow diagram as shown below in figure 1.

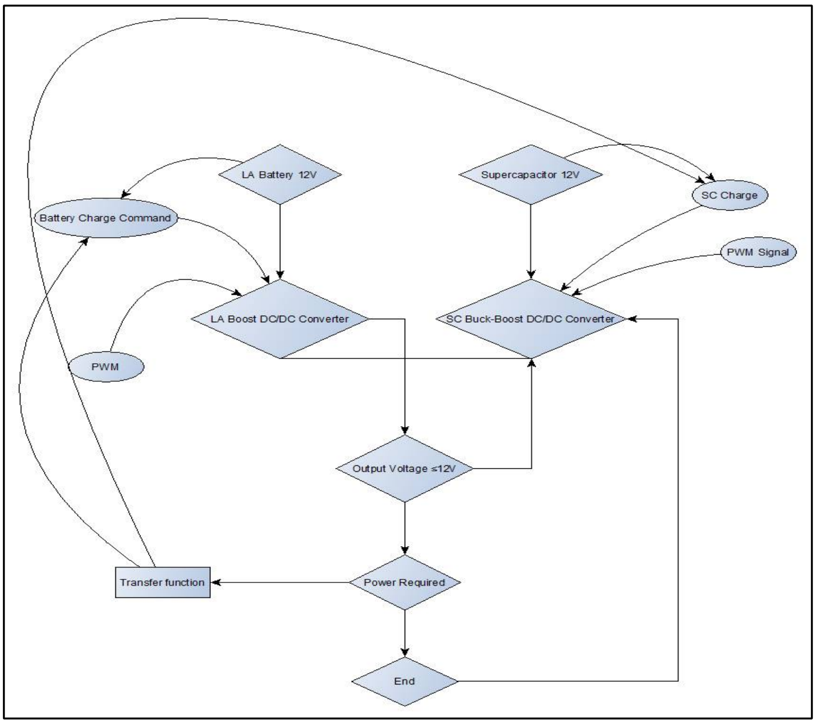

Figure 1 Matlab/Simulink LAB/Supercapacitor Hybrid system based on two DC/DC Converters.

Figure 1 shows the LAB and Supercapacitor hybrid system with two DC/DC converters connected in parallel to the DC Bus. The current provided by both LAB and Supercapacitor are summed to the DC Bus. Hence from the DC Bus the transient currents are fed to the supercapacitor during regenerative braking, which relief the battery from high peak currents. The typical power required for the system is discussed in [16]. The battery converter ensures the battery SOC is kept within limits, whereas the supercapacitor converter ensures that the supercapacitor provides and absorbs high peak current to the DC Bus of the transport vehicle.

3.1. Lead Acid Battery

The lead acid battery output includes; Voltage, Current and State-of-Charge. The LAB voltage is controlled by the boost DC/DC converter, which is connected to the DC bus. The below formulae are used to determine the LABs output characteristics;

$$SOC = \frac{I_{battery}(t)}{3600Q_{battery}} \quad (1)$$

$$I_{battery} = V_{oc}R_{in.battery} \quad (2)$$

$$E_m = Voc - K_e(273 + T_b)(1 - SOC) \quad (3)$$

Where *SOC* is the battery State-of-Charge, *I* is the battery current and *Q* is the battery charge from equation (1). Consequently from equation (2), *Voc* is the battery open circuit voltage and *Rin* is the battey internal resistance. Lastly from (3) *Em* is the electromotive energy, *Ke* is the electron constant and *Tb* is the operating temperature.

The LAB boost DC/DC converter is represented by a flow diagram as shown below in figure 2. The converter is controlled based on Power Width Modulation (PWM) of saw tooth signal. The battery voltage is controlled using a PID which regulates the battery SOC. The saw tooth signal generator of a power width modulator is generated from the specialized technology in control and measurement library under the generator of different signals. The PWM generates a saw tooth waveform, with peak values between +1 and -1. The output of the generator is specified as a time value pair for the simulation. Consequently the PID controller is implemented as a continuous time domain. The derivative of this controller is set to zero and connected in parallel. Figure 2 below illustrate the control strategy of the LABs boost DC/DC converter for ensuring a stable DC output voltage as compared to the reference PWM signal value. Also, figure 3 below shows the initial conditions for this controller is set to execute from external variables, has a zero crossing detection functionality and a compensation which is represented by equation (4). The output of the PID controller is limited to an upper and lower limit of ±1 and treats it as a gain during linearization by the saturation block. The battery characteristics are shown in figure 4.

$$\rho = P + I\frac{1}{s} + D\frac{N}{1+N\frac{1}{s}} \quad (4)$$

Where ρ is the compensation of the PID controller.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 October 2018 doi:10.20944/preprints201810.0135.v1

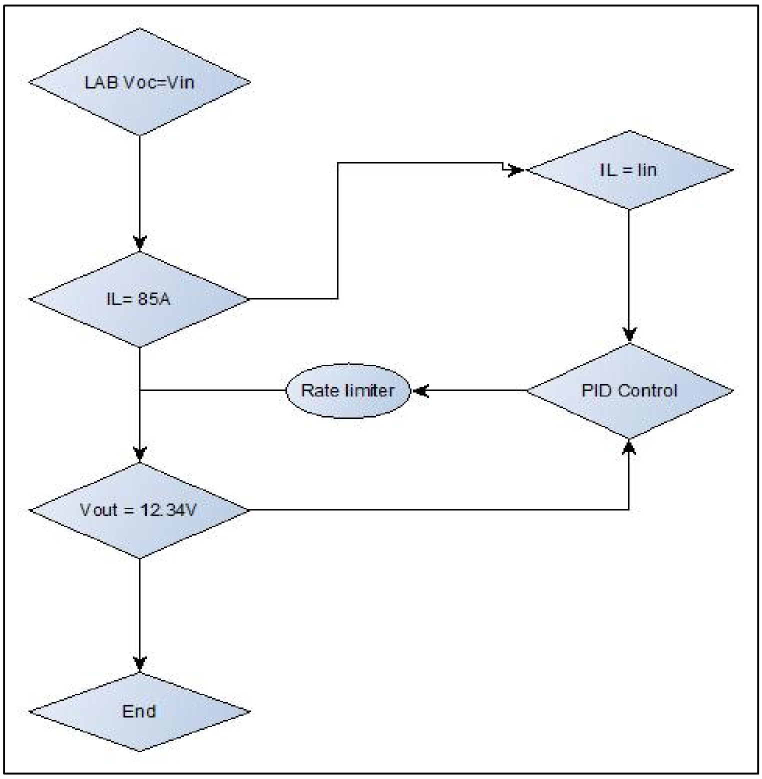

Figure 2 Boost DC/DC Converter for LAB and Control strategy.

The selected battery characteristics are shown in the plotted graph of figure 3 below.

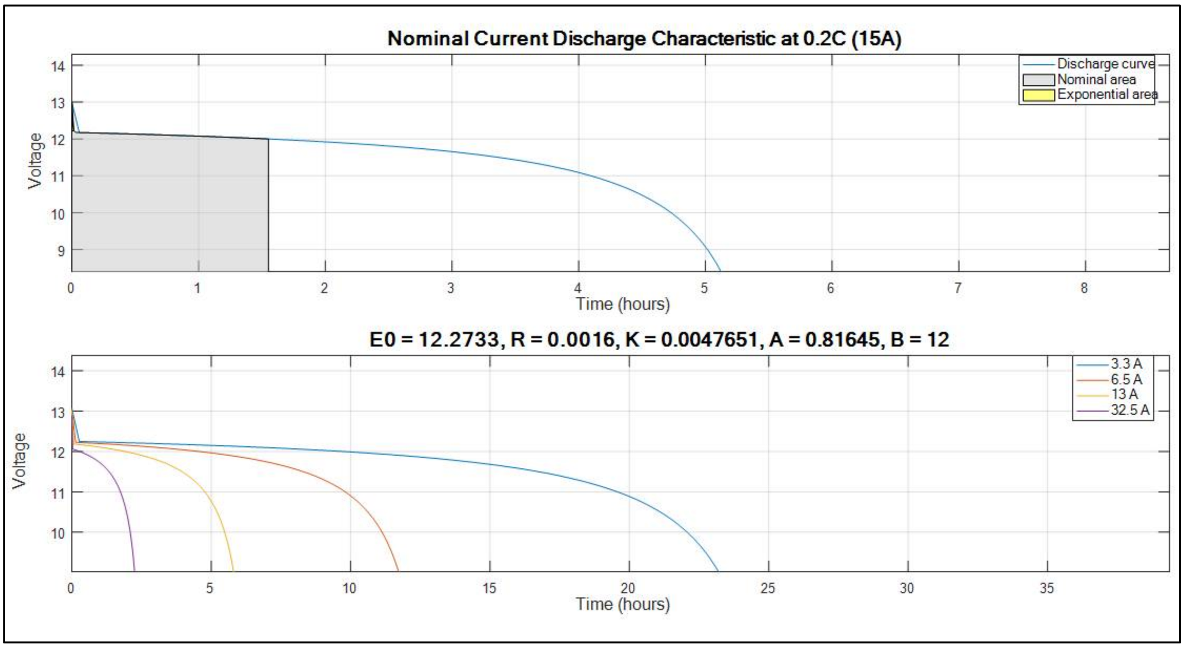

Figure 3 Modelled LAB characteristics.

 doi:10.20944/preprints201810.0135.v1

The graph showing the normal current discharge characteristics indicate that for this selected particular battery, it takes 5.2 hours for this battery to reach a voltage of 0V(SOC=0%) if it is discharged at 0.2C (15A). The battery operates in normal condition between 0-1.5 hours of the time. Moreover, the graph showing several constants, indicate that initially the battery is at 100% SOC, and if it is discharged, at is discharged at different current. Also the graph indicates the requirement for changing the battery if LAB is defective (Operating conditions factors). The assumed current values are indicated on the legend of the graph. The selected battery has the following parameters:

- Open circuit voltage of 12.2733V
- Internal Resistance of 0.0016 Ω
- Performance factors *K* of 0.0047651, *A* of 0.81645 and *B* of 12

This indicates that the battery lasts for 24 hours if it is discharged at 3.3A, which is the lowest in the analysis carried out.

3.2. Supercapacitor

The supercapacitor is modelled and consists of similar output as the LAB, which consist of the terminal voltage, current and the SOC. The supercapacitor model, buck-boost DC/DC converter with control is signified by a flow diagram as shown in figure 4 and 5 below. The supercapacitor discharge characteristics are also shown. The outputs of the supercapacitor are determined according to below formulas;

$$V_{sc}(t) = V_i e^{(-\frac{t}{RC})} \quad (5)$$

$$I_{sc} = \frac{P_{sc}}{V_{sc}} \quad (6)$$

$$SOC = SOC_0 - \int_0^t \frac{\in_f I}{Q} \, dt \quad (7)$$

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 October 2018 doi:10.20944/preprints201810.0135.v1

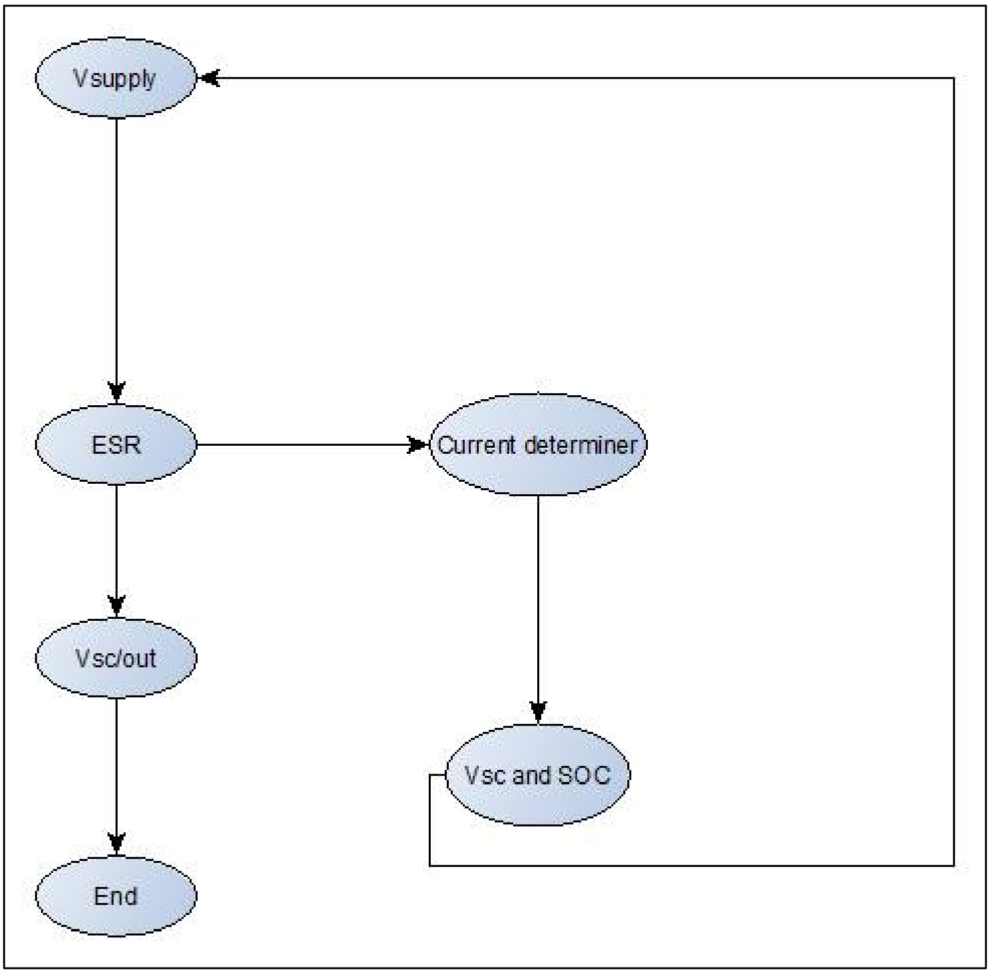

Figure 4 Supercapacitor model developed in Matlab/Simulink.

The supercapacitor model demonstration shown in figure 4 is modelled by using an equivalent circuit model as described in [17]. The voltage of the supercapacitor is obtained by using a controlled voltage source, which is connected to the continuous model for derivation of the Supercapacitor SOC and current. The equivalent DC series resistance is assumed to be ideal. The continuous model developed for determining the Supercapacitor SOC and current includes the summation block for connecting the output of the multiplier and the self-discharge model characteristics, thus integrating the output of the summation added to the initial charge of the supercapacitor (which reflect the formulation of SOC and current). The control strategy of the supercapacitor buck-boost DC/DC converter is described with a flow diagram in figure 5 below, which complement the Simulink model signified by a flow diagram shown in figure 6.

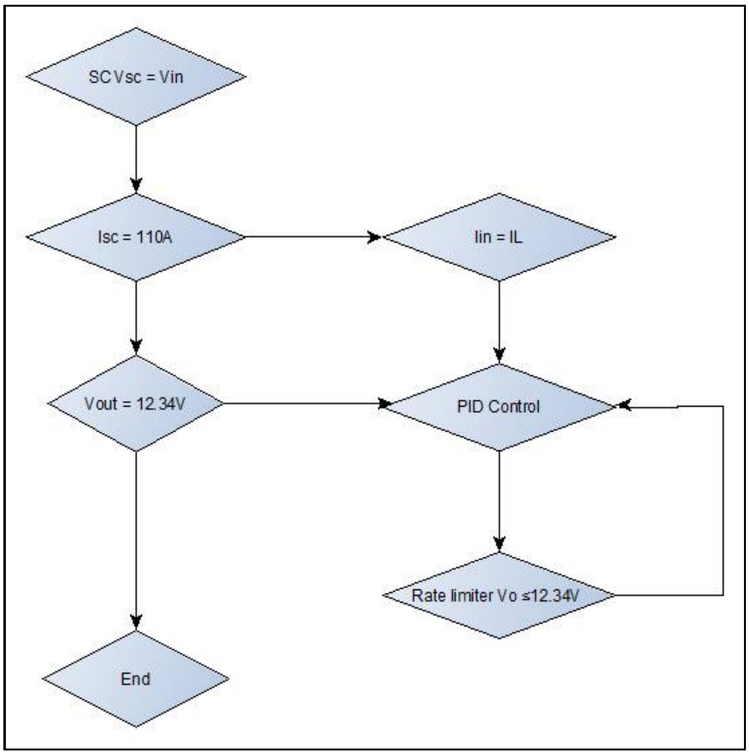

Figure 5 Control strategy of the buck-boost controller for the supercapacitor.

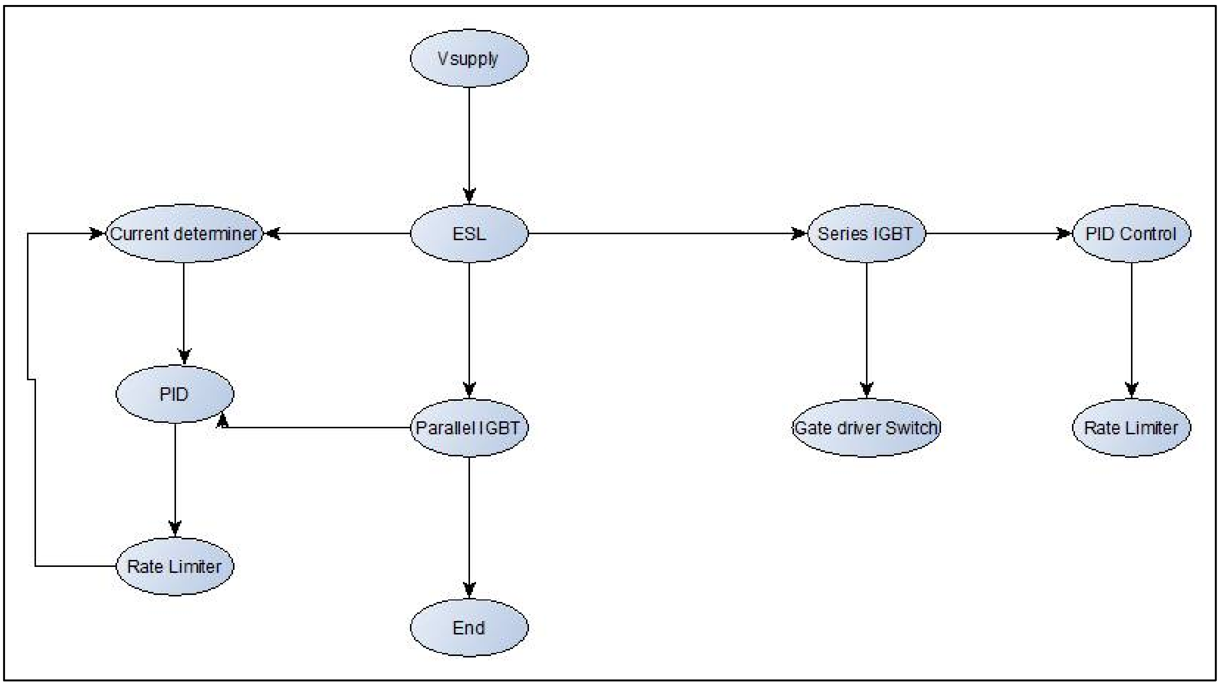

Figure 6 Buck-Boost DC/DC Converter for Supercapacitor control.

The buck-boost converter developed for the supercapacitor as shown in figure 6 consist of two ideal IGBTs to control the current flowing to and from the DC Bus. The switching mechanism of these switches are assumed to be ideal. The PID controller of the converter controls the current and the reference current to the supercapacitor. The PID is operating in continuous mode and developed form in parallel; also it has in internal source and use the similar equation of compensation as described in equation 4. The output of the PID controller is limited by the saturation block to ±1 compared to the PWM signal to be the same or less than the limited value. The converter developed to have the bi-directional power flow (current) to absorb and provide high transient currents due to acceleration and regenerative braking purposes.

The graph showing the supercapacitor characteristics is shown in figure 7.

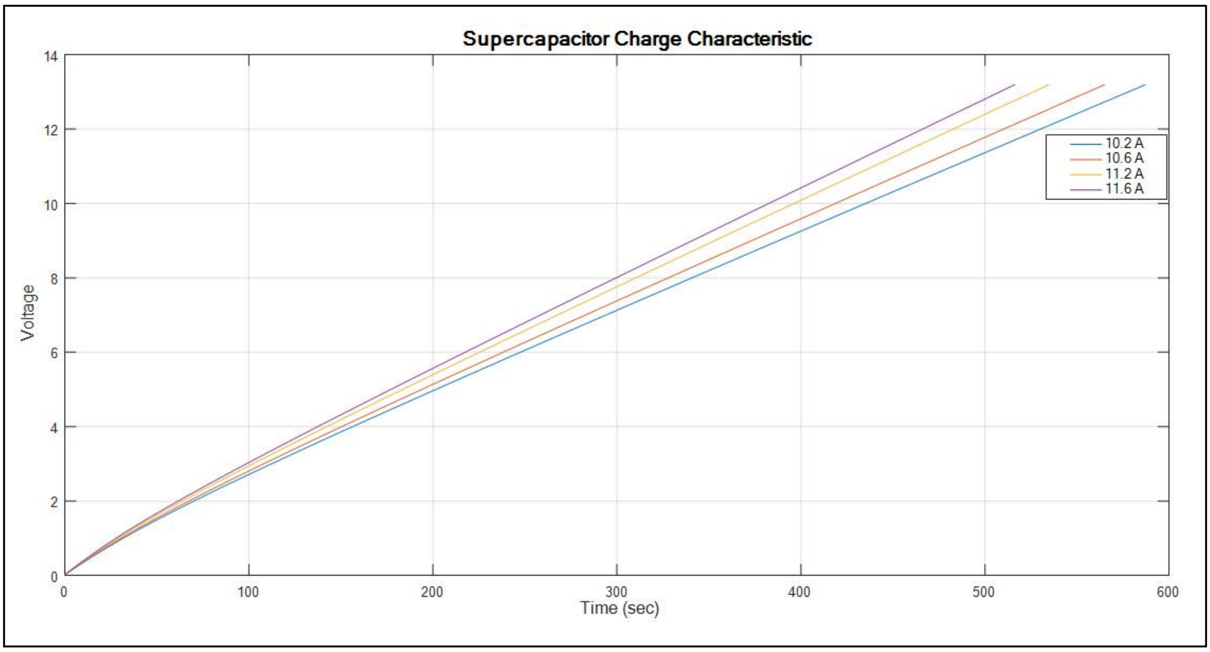

Figure 7 Supercapacitor charge characteristics at 10.2 Ampere.

Figure 6 shows the supercapacitor voltage versus time, which indicates the supercapacitor charge characteristics. The graph indicates that depending on the current size used to charge the supercapacitor that will determine the time it will take to reach 100% SOC. The higher the current, the shorter the duration ~~it takes~~ to fully charge the Supercapacitor. In order to charge this particular Supercapacitor in less than 520 seconds, it needs a current of 11.6A and higher.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 October 2018 doi:10.20944/preprints201810.0135.v1

4. Results and Discussion

The simulation of the results was performed using Matlab/Simulink on a Lenovo Laptop computer with 6GB RAM and a 64-Bit operating system. Hence, in order to ensure that the battery and supercapacitor hybrid system operate to satisfaction, a typical hybrid electric vehicle was used, which is equipped with a 2kW motor. The required current for typical hybrid electric vehicle is compared with current produced by LAB and Supercapacitor. Consequently, the LABs SOC and voltage are kept within 90-95% and 12V. Moreover, the SOC of LAB and Supercapacitor are also evaluated in this simulation study.

The graph showing the voltage versus time of the LAB and Supercapacitor is plotted in figure 8.

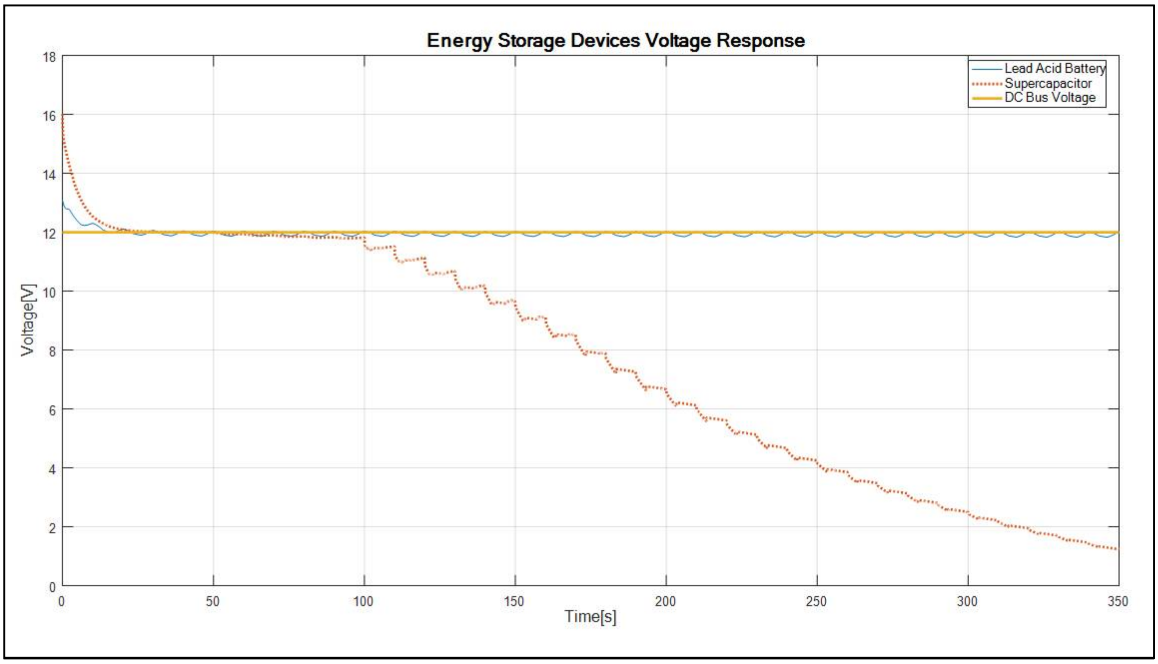

Figure 8 LAB and Supercapacitor Voltage Response.

As shown in figure 8, Lead Acid battery and Supercapacitor shows a decreasing dynamic voltage response between 0-30 seconds when the current is supplied to the DC Bus. Thereafter, the voltage of the LAB becomes constant for the duration of the simulation, whereas the Supercapacitor voltage continues to decrease close to zero after 100 seconds of the simulation. The voltage of the LAB resonates at 12V, which describes better balance battery voltage as described in [18]. As compared to the Supercapacitor’s voltage, the results indicate the dynamic descending response at the beginning of the simulation, whereby after 30s the Supercapacitors voltage merged the LABs voltage. Due to the supercapacitor behavior of being unable to hold a charge for long duration, it is clear from the results that the voltage reached less than 4V from 15.5V. There is 1.6% change in the LAB’s voltage, which offer better system performance as compared to [19],[14]-[20].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 October 2018 doi:10.20944/preprints201810.0135.v1

The plotted graph showing the delivered average current by the LAB and Supercapacitor is shown in figure 9.

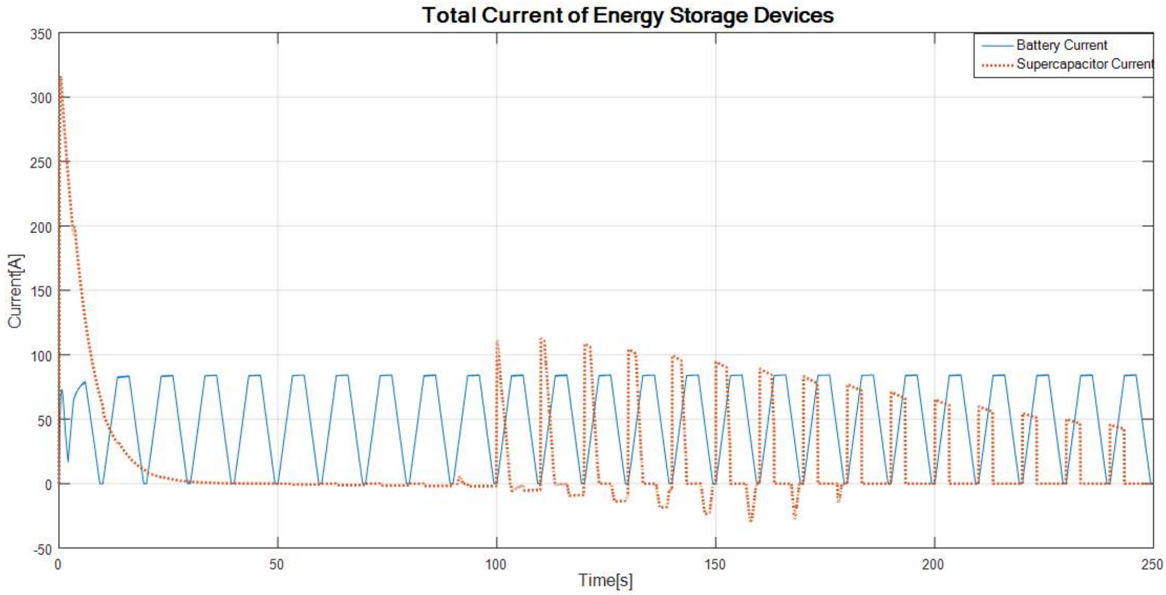

Figure 9 LAB/Supercapacitor hybrid current produced by individual ESD.

As shown in figure 9, the Supercapacitor shows a dynamic decrease response of current between 0-35s of the simulation; thereafter the current is zero until the 100s of the simulation. Hence, the supercapacitor begins charging for the remaining duration of the simulation and reaching the maximum of 110A. Consequently, the LAB supplies a more stable current of about 90A from initial point to the end of the simulation results. The current delivery from both the energy storage device to the DC bus is close to 208 A.,the battery indicate a stable current delivery of approximately 98A and the Supercapacitor fluctuated and reached a maximum of 110A over the simulation period. The fluctuation is caused by charging/discharging of the device. For a 2kW motor, both the devices can meet the motor current demand at a DC bus voltage of 12V. There is a better stability of current provided by the battery, making this topology a better approach system compared to the described in [15],[21]-[22].

The graph describing the power delivered by LAB and Supercapacitor compared to the typical required vehicle power versus time is shown in figure 10.

 doi:10.20944/preprints201810.0135.v1

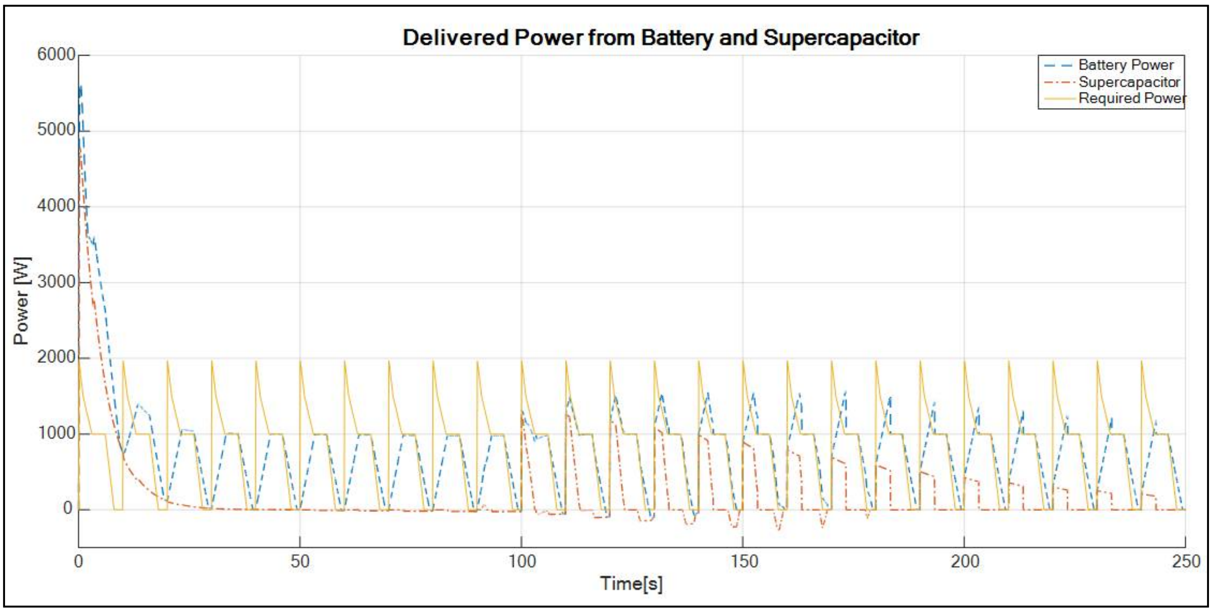

Figure 10 Typical Power delivered by LAB/Supercapacitor Hybrid System versus the required power of hybrid Transport Vehicle.

As shown in figure 10, there is a significant dynamic decrease response of the power delivered to the TVs between the first 25 seconds of the simulation. This is due to high required starting power for a typical hybrid system, which is more than twice the required power. The battery alone is incapable of delivering the required power of a typical hybrid transport vehicle. With the addition of the supercapacitor, the results show that the LAB and Supercapacitor can be connected and deliver the required power to the TV. The behavior of LAB and Supercapacitor of having a dynamic response of high power at the beginning, can indicate the energy storage device initial SOC and can be used to satisfy the hybrid TV demand. It can be seen that in the event where the Supercapacitor is unable to supply the power to the TV, the battery is providing the average power required. There is 9% extra power delivered by the system, making it a better hybrid topology compared to [23]-[24].

The plotted graph showing the battery SOC versus time is shown in figure 11.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 October 2018 doi:10.20944/preprints201810.0135.v1

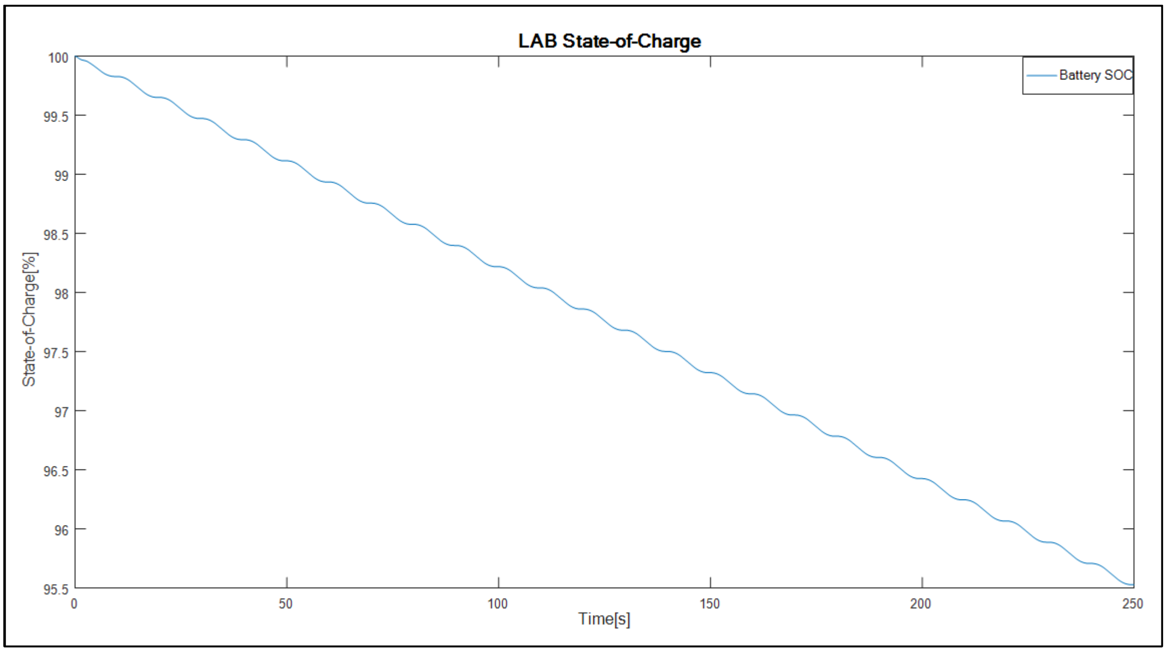

Figure 11 Lead Acid Battery State-of-Charge response.

As shown in figure 11, Lead Acid Battery SOC reduces up to 95% and less and keeps resonating at 92% for the duration of the simulation. This stipulates that the battery is kept at a good SOC limit, as it does not reduce to less than 50%. Consequently, as shown in figure 12, the supercapacitor SOC is stable at between 90-100% for 100 seconds of the simulation study and thereafter, begins to drop as it discharges. Therefore the supercapacitor discharges all the energy and recharges for the next cycle.

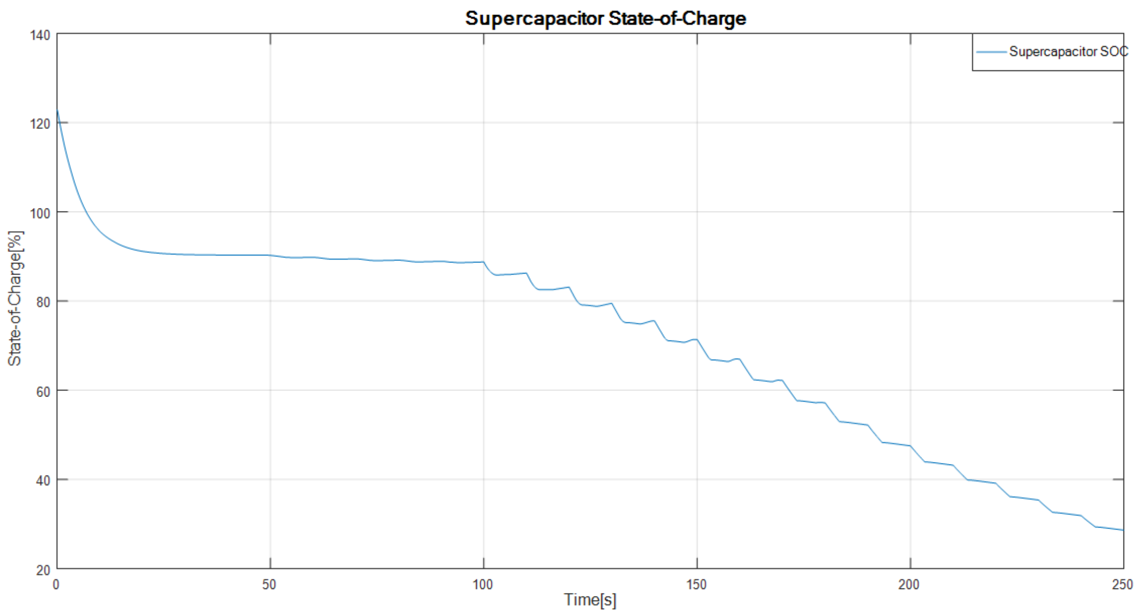

Figure 12 Supercapacitor State-of-Charge response.

The converter algorithm of LAB keeps the battery state-of-charge at 90%. This ensures that the battery is not deeply discharged during operation. The voltage is kept as constant as possible at 12V. This ensures that the battery is not stressed and allows a minimum current to flow through the battery for charging algorithm. As compared to the supercapacitor, it allows high currents to flow through it. The supercapacitor characteristics of having more than 1000 cycles for charge/discharge, allows it to save the battery for deep cycles. Hence, allowing the battery to have endured an enhanced lifespan.

5. Conclusion

The lead acid battery life is highly affected by the way it is charged or discharged. The charging/discharging algorithm for a LAB is developed and indicated that by keeping the battery State-of-Charge above 50% from 0% can positively increase the battery lifespan by connecting the supercapacitor in parallel. The simulation is based on a Matlab/Simulink environment. A typical hybrid vehicle can be powered by the use of lead acid battery and supercapacitor interfaced by the power electronic DC/DC converter. Therefore, by using the topology described in the methodology, the LAB lifespan can be significantly increased with Supercapacitor.

Acknowledgement

The authors would like to thankfully acknowledge the contributions of the Tshwane University of Technology, Pretoria and the Auto-X, Port Elizabeth for providing necessary infrastructure to conduct this research study.

References

[1] M. B. Camara, H. Gualous, F. Gustin, and A. Berthon, "Design and new control of DC/DC converters to share energy between supercapacitors and batteries in hybrid vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 2721–2735, 2008.

[2] M. Al Sakka, H. Gualous, and N. Omar, "Batteries and Supercapacitors for Electric Vehicles," *New Gener. Electr. Veh.*, pp. 135–164, 2012.

[3] A. W. Stienecker, T. Stuart, and C. Ashtiani, "A combined ultracapacitor - Lead acid battery energy storage system for mild hybrid electric vehicles," *2005 IEEE Veh. Power Propuls. Conf. VPPC*, vol. 2005, pp. 350–355, 2005.

[4] N. Hatwar, A. Bisen, H. Dodke, A. Junghare, and M. Khanapurkar, "Design approach for electric bikes using battery and super capacitor for performance improvement," *IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC*, no. Itsc, pp. 1959–1964, 2013.

[5] P. Harrop and H. Zervos, "Batteries , Alternative Storage for Portable Devices," *IdTechEx*, p. 217, 2009.

[6] L. Kouchachvili, W. Yaïci, and E. Entchev, "Hybrid battery / supercapacitor energy storage system for the electric vehicles," *J. Power Sources*, vol. 374, no. June 2017, pp. 237–248, 2018.

[7] B. Vulturescu, S. Butterbach, C. Forgez, G. Coquery, and G. Friedrich, "Ageing study of a supercapacitor-battery storage system," *19th Int. Conf. Electr. Mach. ICEM 2010*, 2010.

[8] S. Sreedhar, J. B. Siegel, and S. Choi, "Topology Comparison for 48V Battery-Supercapacitor Hybrid Energy Storage System," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 4733–4738, 2017.

[9] E. Ferg, C. Rossouw, and P. Loyson, "The testing of batteries linked to supercapacitors with electrochemical impedance spectroscopy: A comparison between Li-ion and valve regulated lead acid batteries," *J. Power Sources*, vol. 226, pp. 299–305, 2013.

[10] A. Castaings, W. Lhomme, R. Trigui, and A. Bouscayrol, "Comparison of energy management strategies of a battery/supercapacitors system for electric vehicle under real-time constraints," *Appl. Energy*, vol. 163, 2016.

[11] S. Fiorenti *et al.*, *Modeling and experimental validation of PbA battery - Supercapacitor energy storage system ?*, vol. 7, no. PART 1. IFAC, 2013.

[12] H. . Liu, D. . Maly, and Z. . Wang, "Supercapacitor and lead-acid battery hybrid and improved diesel engine cold cranking," *IET Conf. Publ.*, no. 538 CP, pp. 199–203, 2008.

[13] W. F. Infante, A. F. Khan, N. J. C. Libatique, G. L. Tangonan, and S. N. Y. Uy, "Performance evaluation of series hybrid and pure electric vehicles using lead-acid batteries and supercapacitors," *TENCON 2012 - 2012 IEEE Reg. 10 Conf.*, pp. 1–5, 2012.

[14] a Jarushi and N. Schofield, "Modelling and Analysis of Energy Source Combinations for Electric Vehicles .," *World*, vol. 3, pp. 1–7, 2009.

[15] N. Omar, J. Van Mierlo, F. Van Mulders, and P. Van den Bossche, "Assessment of

 doi:10.20944/preprints201810.0135.v1

Behaviour of Super Capacitor-battery System in Heavy Hybrid Lift Truck Vehicles," *J. Asian Electr. Veh.*, vol. 7, no. 2, pp. 1277–1282, 2009.

[16] M. J. Lencwe, "Performance Studies of Lead Acid Batteries for Transport Vehicles," pp. 528–532, 2017.

[17] M. Ceraolo, G. Lutzemberger, and D. Poli, "State-Of-Charge Evaluation Of Supercapacitors," *J. Energy Storage*, vol. 11, pp. 211–218, 2017.

[18] M. Daowd, N. Omar, P. van den Bossche, and J. van Mierlo, "A review of passive and active battery balancing based on MATLAB/Simulink," *Int. Rev. Electr. Eng.*, vol. 6, no. 7, pp. 2974–2989, 2011.

[19] V. Tibude and S. G. Tarnekar, "Co-Working of Solar Panel – Battery – Super capacitor for Electric Vehicle," vol. 2, no. 3, pp. 7–13, 2016.

[20] L. H. Seim, "Modeling, Control and Experimental Testing of a Supercapacitor/Battery Hybrid System - Passive and Semi-Active Topologies," 2011.

[21] M. Wieczorek and M. Lewandowski, "HYBRID ENERGY STORAGE SYSTEM FOR ELECTRIC VEHICLES HYBRYDOWY ZASOBNIK DO ZASTOSOWANIA," 2016.

[22] S. D'Arco, D. Iannuzzi, E. Pagano, and P. Tricoli, "Energy management of electric road vehicles equipped with supercaps," *VDI Berichte*, no. 1852, pp. 507–519, 2004.

[23] M. Passalacqua, D. Lanzarotto, M. Repetto, and M. Marchesoni, "Advantages of Using Supercapacitors and Silicon Carbide on Hybrid Vehicle Series Architecture," *Energies*, vol. 10, no. 7, p. 920, 2017.

[24] A. Lahyani, A. Sari, I. Lahbib, and P. Venet, "Optimal hybridization and amortized cost study of battery/supercapacitors system under pulsed loads," *J. Energy Storage*, vol. 6, pp. 222–231, 2016.