PERFORMANCE STUDY OF SUPERCAPACITOR-BATTERY INTEGRATION SCHEME FOR ENERGY STORAGE SYSTEM

Nasrur Rasyadi Md Rafie & Zulkarnain Ahmad Noorden

Institute of High Voltage and High Current, Faculty of Electrical Engineering,

Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

zulkarnain-an@utm.my

ABSTRACT

The paper proposes a new integration scheme between supercapacitor (SC) and battery as energy storage system (ESS) for electric vehicle. Even though there are several researches have been conducted to improve the quality or performance of ESS such as using hybrid fuel cell, solar and fast charging ESS, the findings in this paper are significant in providing an alternative practical design of SC-battery integration scheme. SC and battery were integrated in parallel connection with the aid of direct current (DC) converters; boost converter for the battery and bidirectional converter for the SC. It was found that the SC was capable in providing higher rate of power during an extreme change of power demand. In contrast, the battery was capable of complementarily supplying stable power in accordance to peak power profile of demand.

1. INTRODUCTION

Battery storage system is being used as an energy supply of electric vehicles. Battery can give high-energy output when the vehicle is moving. The battery can be recharged during the regenerative braking [Noshin, et al. (2009)]. The drawbacks of battery are obviously that the poor traits of low temperature, low life cycle and low power density [Yu, et al. (2009)]. The ideal requirements for an energy storage system (ESS) are high energy density, high power density and excellent discharge capability. If the battery capacity is increased to meet the power demand, the cost and weight of electric vehicles will be increased [Hayet, et al. (2011) & Hengbing, et al. (2010)]. In other term, the weakness found in battery energy storage being the main barrier to commercialized superb technology of electric vehicle.

Thus, supercapacitor (SC) should be introduced to solve this matter by coming up with SC-battery storage system to achieve higher power density, higher energy density and much longer battery lifetime. The reason to combine battery with SC is due to SC stores charge in faster rate inside its structure. During discharging, electrons rapidly leaving through the terminal without having undergone slow chemical reactions process.

Although the SC-battery can improve the performance of ESS, the power distributed between these two components must be controlled. The paper proposes a new integration scheme of SC-battery as ESS for electric vehicle. Study on the integration scheme in terms of its power delivery, current behavior and state-of-charge were carried out via MATLAB software through Simulink program.

2. DESIGN OF SUPERCAPACITOR-BATTERY INTEGRATION SYSTEM

In this paper, the simulation configuration was in accordance to the SC-battery integration model as shown in Fig. 1. The model is designed to have two DC converters, one converter for each of individual energy source so that the power distribution between the SC and battery can be controlled. Not only that, the battery performance is improved via this configuration since the DC bus voltage is more stable [Xiang, et al. (2014) & Aree, et al. (2014)]. Fig. 2 shows the overall system of SC-battery integration. The detail configuration in each block – for the Energy Management System for ESS, the Electric Vehicle Motor, the ESS Bidirectional DC-DC Converter and the ESS Boost Converter – in Fig. 2 are illustrated in Fig. 3(a) to 3(d).

2.1 Model of Supercapacitor and Lithium Ion Battery

As shown in Fig. 2, the SC model used in this project was referred to Maxwell K2 series ultra-capacitor BCAP0650 with a capacity of 650 F. The main

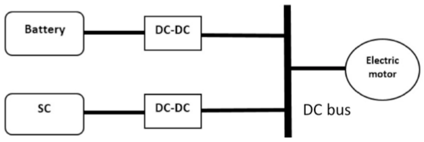

Fig. 1. Supercapacitor-battery integration scheme.

parameters of SC were set as in Table 1. Referring to Fig. 2, the applied rating of the battery nominal voltage was in the range of 12 to 265 V for the simulation according to the previous studies [Aree, et al. (2013)]. Therefore, the rating of the battery nominal voltage was set to 28 V. All the parameters of the battery are also tabulated in Table 1.

2.2 Designing Boost Converter

A boost converter was applied on Li-ion battery to step up its output voltage equal to the DC bus voltage, as illustrated in Fig. 3(a). Table 1 displays design criteria for the boost converter. Based on what had been listed in the table, the value of duty cycle D of 0.377, inductor L of 21.11 mH, average inductor current I_L of 0.902 A and capacitor C of 424.12 μF for boost converter were calculated. The inductance value obtained from the calculation was the minimum inductor value required by the boost converter to fulfill the 5 % ripple current criteria. For a better simulation result of making the ripple practically smaller, the inductance value was further increased as much as 25 % so that it became L = 26.39 mH [Hart (2011)].

2.3 Designing Bidirectional Converter

On the other hand, as shown in Fig. 3(b), the SC was connected to bidirectional converter. Table 1 also tabulates the design criteria for the bidirectional converter. The same method was used to obtain the duty cycle, inductor, capacitor and average inductor current of bidirectional converter. Their values were D = 0.644, I_L = 1.58 A, L = 25.75 mH and C = 724.5 μF. This bidirectional converter then was combined with boost converter in parallel connection so that the SC and battery could be integrated.

In order to provide two-direction of energy flow from the sources – as shown in Fig. 2 and 3(c) – a dynamic load was selected by utilizing a “DC Source” block to represent as a DC Bus or Motor. The existence of DC source as the DC Bus could be an analogy for the electric vehicle motor, which was to comply with the classical theory of electrical machines where the

Table 1 Design criteria for the supercapacitor, battery, bidirectional converter and boost converter.

Supercapacitor	Battery	Bidirectional Converter	Boost Converter
C = 650 F	$V_{nominal}$ = 28 V	V_s = 16 V	V_s = 28 V
ESR = 2.1 mΩ	Capacity = 6600 mAh	V_o = 45 V	V_o = 45 V
$V_{initial}$ = 16 V	$SOC_{initial}$ = 100	f_s = 10 kHz	f_s = 10 kHz
	$R_{internal}$ = 42.42 mΩ	ΔI_L = 5%	ΔI_L = 5%
		ΔV_L = 5%	ΔV_L = 5%
		R = 80 Ω	R = 80 Ω

*C is the capacitance, ESR represents the equivalent series resistance, $V_{initial}$ is the initial voltage, $V_{nominal}$ is the nominal voltage, $SOC_{initial}$ represents the initial state-of-charge, $R_{internal}$ is the internal resistance, V_s is the input voltage, V_o is the output voltage, f_s denotes as the switching frequency, ΔI_L is the inductor current ripple, ΔV_L represents the output voltage ripple and R is the load.

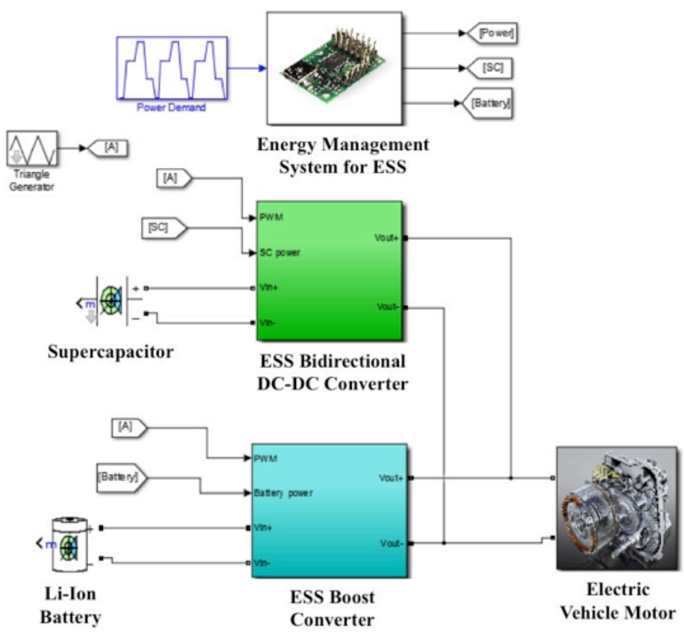

Fig. 2. The supercapacitor-battery integration system

generated voltage or back electromotive force is being symbolized as a voltage source.

2.4 Control System of DC-DC Converter

The "Power Demand" block in Fig. 2 is taken from "Repeating Sequence" block diagram that can be specified its time values and output values. It represented the load profile of the electric vehicle in term of power. It was assumed that the increasing power demand showed the electric vehicle was accelerating while decreasing power demand meant it was decelerating.

Fig. 2(d) is the model used to limit the rate of battery power supplied to the load. The power demand had to pass through the "Rate Limiter" block before sending the signal to the boost converter that connected to battery. This "Rate Limiter" block would restrict the power drawn from battery and was set to be 300 W/min. Meanwhile, the SC power was subtraction of battery power from the demand profile.

The switches of both converters should be controlled on certain sequence to produce a Pulse Width Modulation (PWM) on their switching. Hence, as depicted in Fig. 2, a triangular signal was generated from "Triangle Generator" block to be a carrier signal to control the switching frequency. While the error current signal, obtained from the different of inductor current and current value of the power demand, was used as the reference waveform. These both signals are compared by passing them through "Comparator" block before entering the switches. They are illustrated in Fig. 2(a) and 2(b).

3. RESULTS AND DISCUSSION

Fig. 4(a) indicates the power required by the load or motor to enable the electric vehicle to move. The power demand value was zero at the beginning and started to increase from 0 to 1000 W after 2 minutes. It was assumed that the electric vehicle began to move at t = 1 min, consuming 1000 W power from the SC-battery source. The power demand was remain constant until it was further increased to be 1500 W at t = 6 min, indicated that the electric vehicle was accelerating. Next, the power demand decreased to 500 W or the electric vehicle decelerated 3 minutes later and finally stopped moving at t = 12 min.

It can be obviously seen from Fig. 4(b) that the power generated by SC-battery able to follow the pattern of power demand, fulfilling the load requirement. From the figure, it is found generally that SC would supply a faster response of power when there had a rapid change of demand, whereas the battery gave a steady response of base power required [Xiang, te al. (2014)]. The quick response of SC was caused by the bidirectional converter that operated in boost mode once it detected a positive slope of power demand profile. The SC would always remain in idle state if there had no transient of power demand. The power of SC and battery were obtained by multiplying their voltage and current respectively.

During the deceleration, the braking energy was transferred back from motor to the SC. This enable the SC to increase its state-of-charge as a result of buck

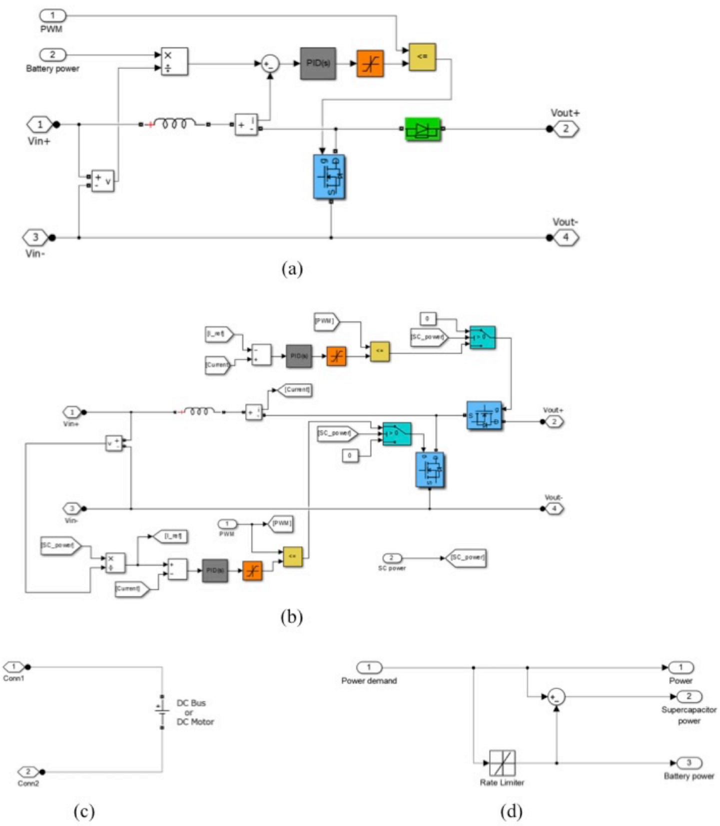

Fig. 3. Configuration inside each block of (a) ESS Boost Converter, (b) ESS Bidirectional DC-DC Converter, (c) Electric Vehicle Motor and (d) Energy Management System for ESS.

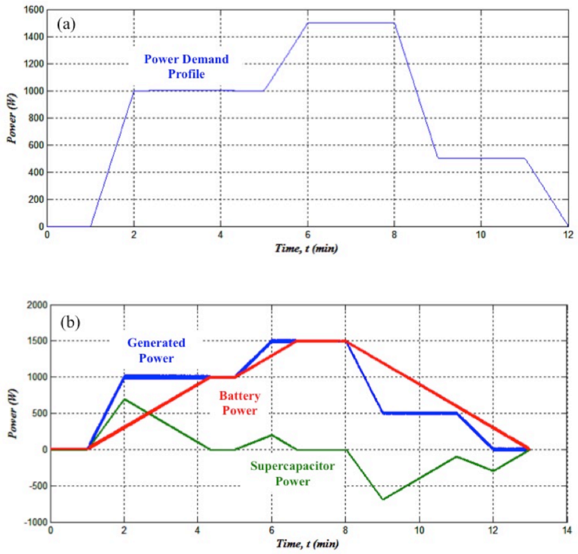

Fig. 4. (a) Power demand profile on load side and (b) Total power generated from integration of SC-battery

mode operation by bidirectional converter after it sensed a negative slope of power demand profile. While the SC was charging up, the battery reduced its power rate accounted for -300 W/min until it reached zero value. The reason for battery power drop dramatically to zero at phase of deceleration because no power was needed by motor when electric vehicle slowed down or stopped moving. These findings suggest that the simulated model has successfully integrated SC and battery – connected to a bidirectional DC-DC converter and a boost converter, respectively – in a such way that capable of complementing each other in terms of providing demanded power by the load of an electric vehicle. The SC was capable of providing higher rate of power during an extreme change of power demand. In contrast, the battery was capable of complementarily supplying stable power in accordance to peak power profile of demand.

4. CONCLUSION

In a conclusion, the integration of SC-battery scheme presented in the paper is able to generate dynamic power transient according to the load demand, where the low power density of the battery is supported by high power density from the SC. The boost converter and bidirectional converter are applied to the battery and SC respectively in order to control their dynamic response towards the demand profile.

ACKNOWLEDGEMENT

The authors acknowledge the financial support from Universiti Teknologi Malaysia (Q.J130000.2723.01K09) and the Ministry of Education Malaysia (R.J130000.7809.4F613).

REFERENCES

Aree Wangsupphaphol, Nik Rumzi Nik Idris, Awang Jusoh, Nik Din Muhamad, Deceleration-based Design Auxiliary Power Source for Electric Vehicle Application, *Engine*, University of Waterloo, 2014.

Aree Wangsupphaphol, Nik Rumzi Nik Idris, Awang Jusoh, & Nik Din Muhamad, Power Converter Design for Electric Vehicle Applications, *Jurnal Teknologi*, Volume 3, 25-31, 2013.

Hart, D. W., Power Electronics (International Edition). New York, America: McGraw-Hill, 2011.

Hayet Slimani Khaldi, Ahmed Chibeb Ammari, Design & Comparison of Two DC Converter Interfacing Hybrid ESS to DC Bus, *International Conference on Control, Engineering & Information Technology*, 2011.

Hengbing Zhao, Andrew Burke, Fuel Cell Vehicle Using Supercapacitors, *Institute of Transportation Study*, University of California, 2010.

Noshin Omar, Joeri Van Mierlo, Frederik Van Mulders, & Peter Ven Bossche., Assessment of Behaviour of Super Capacitor-battery System in Heavy Hybrid Lift Truck Vehicles. *Journal of Asian Electric Vehicles*, Volume 7, 1277-1282, 2009.

Xiang Changle, Wang Yanzi, Hu Sideng, & Wang Weida, A New Topology and Control Strategy for a Hybrid Battery-Ultracapacitor Energy Storage System. *Energies, 7*, 2874 – 2896, 2014.

Yu Zhang, & Jiang Zhenhua, Dynamic Power Sharing Strategy for Active Hybrid Energy Storage System, *Vehicle Power and Propulsion Conference,* 558-563, 2009.

Nasrur Rasyadi Md Rafie received the Bachelor Degree of Electrical Engineering from University of Technology Malaysia (UTM), in 2015. He is currently working with Energy Commission of Malaysia as a Junior Executive Engineer at Department of Industrial Development & Electricity Market Regulation. His research interests are power system analysis and energy storage technology.

Zulkarnain Ahmad Noorden received the Ph.D. degree in electrical engineering from Shibaura Institute of Technology Japan in 2013. He is currently works at Universiti Teknologi Malaysia (UTM) as a senior lecturer. His research interests include energy storage system and power equipment diagnosis.