Journal of Innovative Technology, Vol. 2, No. 2, pp. 31-38, September 2020
http://doi.org/10.29424/JIT.202009_2(2).0005

Modeling and Verification of a Hybrid Energy Storage System for Electric Vehicle

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ABSTRACT

This research reported here aimed to implement a hybrid energy storage system (HESS) for electric vehicles by integrating a non-isolated bidirectional converter with lithium batteries and supercapacitors as a hybrid power module. This was to reduce the complexity of feedback circuit, to implement a system control based on load power demand, to achieve system simplification and reduce costs. Moreover, the energy change on the supercapacitor was used to estimate the load power, and the impact caused by non-ideal components was also considered to achieve accurate load power estimation, thereby reducing the component counts that detects the load power. Furthermore, a rule-based control strategy based on the average load power and the supercapacitor voltage was employed from the following perspectives: (1) to implement a hybrid energy storage system with multiple working modes to reduce the losses caused by the energy consumed between the battery and supercapacitor; (2) to effectively reduce the battery current stress; and (3) to better extend the battery life. In addition, a hysteresis control strategy was adopted as well to not only store more energy in the supercapacitors but also stabilize the DC bus voltage. Finally, a system platform was established because the feasibility of the hybrid energy storage system was verified with simulation and experiment results.

Keywords: Hybrid energy storage system, lithium battery, supercapacitor, rule-based control strategy.

1. INTRODUCTION

Energy storage systems used in electric vehicles can provide energy to drive electric vehicle motors. However, when electric vehicles accelerate, climb, and go into regenerative braking, the high power changes generated can be regarded as pulsed loads and this will cause higher stress and impact on the energy storage system. Also, this may cause the energy utilization rate of the energy storage system to become low, the cell temperature to rise, the life cycle to be shortened and other related problems. Since this pulsed load current can be decomposed into DC and AC components, the magnitude of the AC component current and the AC frequency has a significant impact on battery aging, and so affects the energy loss caused by the battery's equivalent series resistance (Breucker *et al.* 2013; Uddin *et al.* 2016; Jacobs *et al.* 1963).

Although lithium batteries, regarded as the main energy source of the energy storage system, have a high energy density and can provide continuous and stable energy their power density is still insufficient. Therefore, the pulsed load generated by electric vehicles may cause batteries to undergo discharge overcurrent, and then affects the lifespan of the batteries. In order to overcome the problem of insufficient power density of a pure battery energy storage system, a hybrid energy storage system composed of a composite energy storage device can better enable the energy storage system to have both high energy density and high power density characteristics. This optimal system can greatly extend the system life, increase energy utilization, and reduce system costs.

In terms of hybrid energy storage systems, only one energy storage device is directly connected to the load DC bus (Wang *et al.* 2017; Wang *et al.* 2015; Ibanez *et al.* 2019; Kuperman *et al.* 2013; Cao *et al.* 2012; Dusmez *et al.* 2015; Kouchachvili *et al.* 2018; Peng *et al.* 2004; Wang *et al.* 2017). As far as the proposed hybrid energy storage system is concerned, the battery is not directly connected to the load to better avoid the lithium battery outputting high power instantaneously. Instead, a supercapacitor is used as an energy buffer to absorb high pulsed energy. The battery is connected to the DC bus via a bidirectional power converter, so that the energy stored in the lithium battery would not be limited by the motor operating voltage. Within the circuit gain range, even if the lithium battery is in a relatively non-linear area, it could still supply power stably. That is because this system architecture reduces the energy supplied by a lithium battery to a pulsed load, and so a lower power bidirectional converter could be used.

Therefore, the system proposed in this paper is intended to not only achieve voltage matching between lithium batteries and supercapacitors through a bidirectional power converter but also optimize the characteristics of traditional energy storage systems through energy management strategies so as further to improve the energy efficiency of energy storage systems, increase the available capacity of energy storage devices, increase system energy density, increase system power density, and reduce system cost and volume.

2. MAIN CIRCUIT AND OPERATING MODE OF THE PROPOSED HYBRID STORAGE SYSTEM

The circuit architecture of the proposed hybrid storage system is illustrated in Fig. 1. The proposed system consists of a MCU (dsPIC33FJ64GS606), a bidirectional converter, a gate driver, a signal (voltage and current) capturing circuit, a lithium battery module, and a supercapacitor module.

Manuscript received June 24, 2020; revised July 7, 2020; accepted July 12, 2020.
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The proposed system architecture has the following characteristics. First, the battery voltage is independent of the load voltage, and so the energy stored in the battery can be used in a full range. Only the average power required by the load is transferred through the bidirectional converter. Therefore, the current stress can be significantly reduced, and the bidirectional converter only needs to be designed with the rated power of the battery's maximum power output so as to better reduce the volume and weight of the bidirectional converter. Secondly, the supercapacitors are directly connected to the DC bus of the load, and they are responsible for both the rapid change of load power and the instantaneous high power output required to provide the load. In addition, the supercapacitors can effectively absorb the energy recharge when the motor works in the energy regenerative braking mode, which can avoid frequent charge and discharge of the battery module, and so when the subsequent need to provide load energy, the supercapacitors directly provide the load energy to reduce energy losses between the load and the battery module.

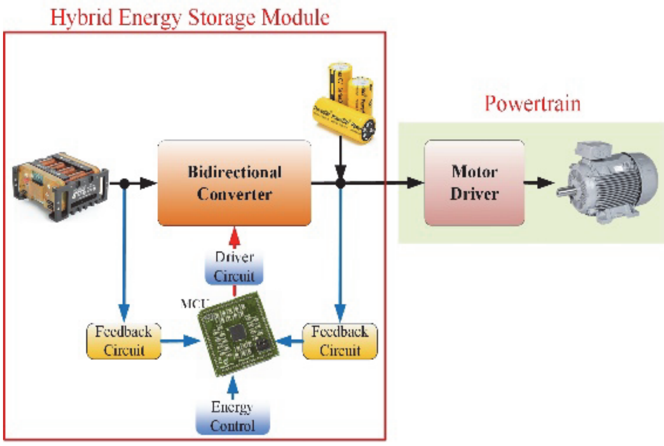

Fig. 1 System architecture of the proposed hybrid storage system.

In order to reduce the volume and the system losses, to increase the power density, and to achieve the energy management between the battery module and the supercapacitor module, a non-isolated buck/boost bidirectional converter was employed as the main circuit, where a power diode is added and directly connected between the battery module and the supercapacitor module, as shown in Fig. 2. When the bidirectional converter works normally, the battery module supplies energy to the motor driver through the bidirectional converter within an average power. In the case of continuous high power output, when the voltage of the supercapacitor module and the DC bus drops to the voltage level of the battery module, the battery module will directly supply energy to the motor driver through the diode. Given the above, this behavior can avoid the bidirectional converter in an uncontrollable state and avoid that the high load current flows through the inductor and the power switches, which not only reduces the possibility of inductor saturation but also reduces losses caused by circuit impedance, such as switch conduction loss, inductance parasitic resistance loss, etc.

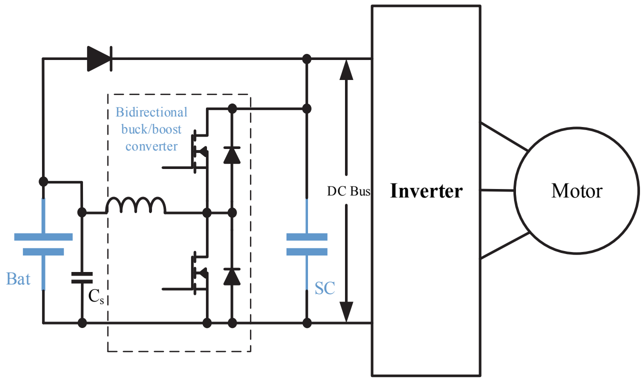

Fig. 2 Main circuit of the proposed hybrid storage system.

In order to obtain the power demand of the electric vehicle's energy storage system under different speed and acceleration conditions, the built-in model of MATLAB was used to simulate the electric vehicle system, as shown in Fig. 3. This complete electric vehicle model can be simulated by running UDDS (Urban Dynamometer Driving Schedule) to obtain the actual load power curve required by the electric vehicle. To verify the feasibility of the control strategy of the hybrid energy storage system, the load power curve was reduced proportionally, as shown in Fig. 4, where the maximum load power is reduced to 1.25 kW, and the maximum regenerative braking power is −0.72 kW. In general, the maximum transient load power was about three times the rated power. Therefore, the load power curve can be used to simulate a motor load with a rated power of 400 W ~ 500 W.

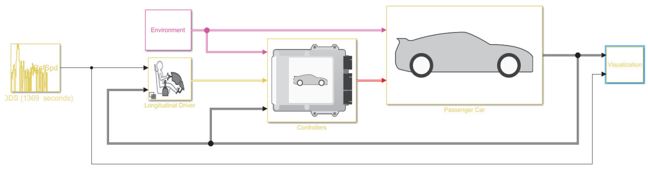

Fig. 3 System simulation for electric vehicle based on the UDDS power curve.

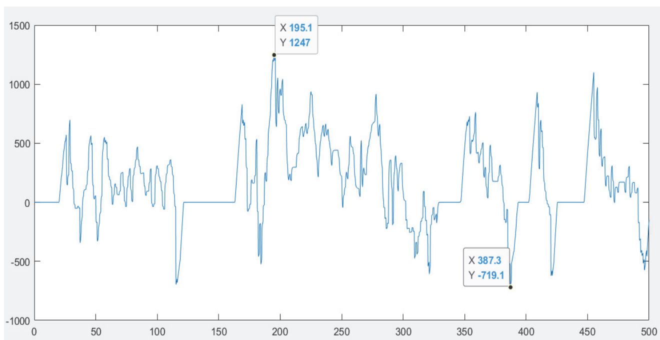

Fig. 4 The reduced-scale UDDS power curve.

Figures 5(a)-(f) are the working modes of the hybrid energy storage system under different load conditions. The operation of the hybrid energy storage system can be divided into four modes, where Fig. 5(a) is a pure battery power supply mode. Figs. 5(b)-(c) are hybrid power supply modes, Fig. 5(e) is pure supercapacitor regenerative braking energy absorption mode, and Figs.

5(d) and 5(f) are hybrid regenerative braking energy absorption. Given the above, the working mode is distinguished according to whether the maximum power P_{conv} of the bidirectional converter can meet the demand of the load power P_{dem}, and the level of the supercapacitor module voltage V_{sc}. For example, as shown in Fig. 5(a), when the battery module directly transfers energy to the load through the power diode, this state is that the hybrid energy storage system has been in the situation of $P_{dem} > P_{conv}$ for a long time. So, the supercapacitor module voltage has dropped to the battery module at the same voltage level, and the controller stops the bidirectional converter at this time to protect the bidirectional converter from working under the condition of $P_{dem} = P_{conv}$. Moreover, when the load power gradually decreases to $P_{conv} > P_{dem}$, the battery energy can pass through the bidirectional converter to provide the load and supercapacitor module separately, as shown in Fig. 5(b). At this time, the voltage V_{sc} of the supercapacitor module will gradually increase. Furthermore, as shown in Fig. 5(c), the battery module charges the load and the supercapacitor module via the bidirectional converter at the same time, and $P_{dem} > P_{conv}$ at this time, the supercapacitor module is responsible for supplying the energy of the high-frequency pulsed component, and the battery module provides the average energy required by the load; In addition, Fig. 5(d) shows the battery module and load current needed to charge the supercapacitor module. When the load is in the state of regenerative braking energy recovery, and the supercapacitor module voltage is in a lower voltage level, the supercapacitor module voltage will gradually rise at this time. When the threshold voltage is reached, the battery module will stop supplying energy, as given in Fig. 5(e). Subsequent energy supply or absorption is directly responsible for the supercapacitor module, and when the regenerative braking energy of the load is continuously recovered to the supercapacitor module, the supercapacitor module reaches the upper limit voltage. Thereby, the bidirectional converter will be started to return energy to the battery module to maintain the supercapacitor module voltage in a safe range.

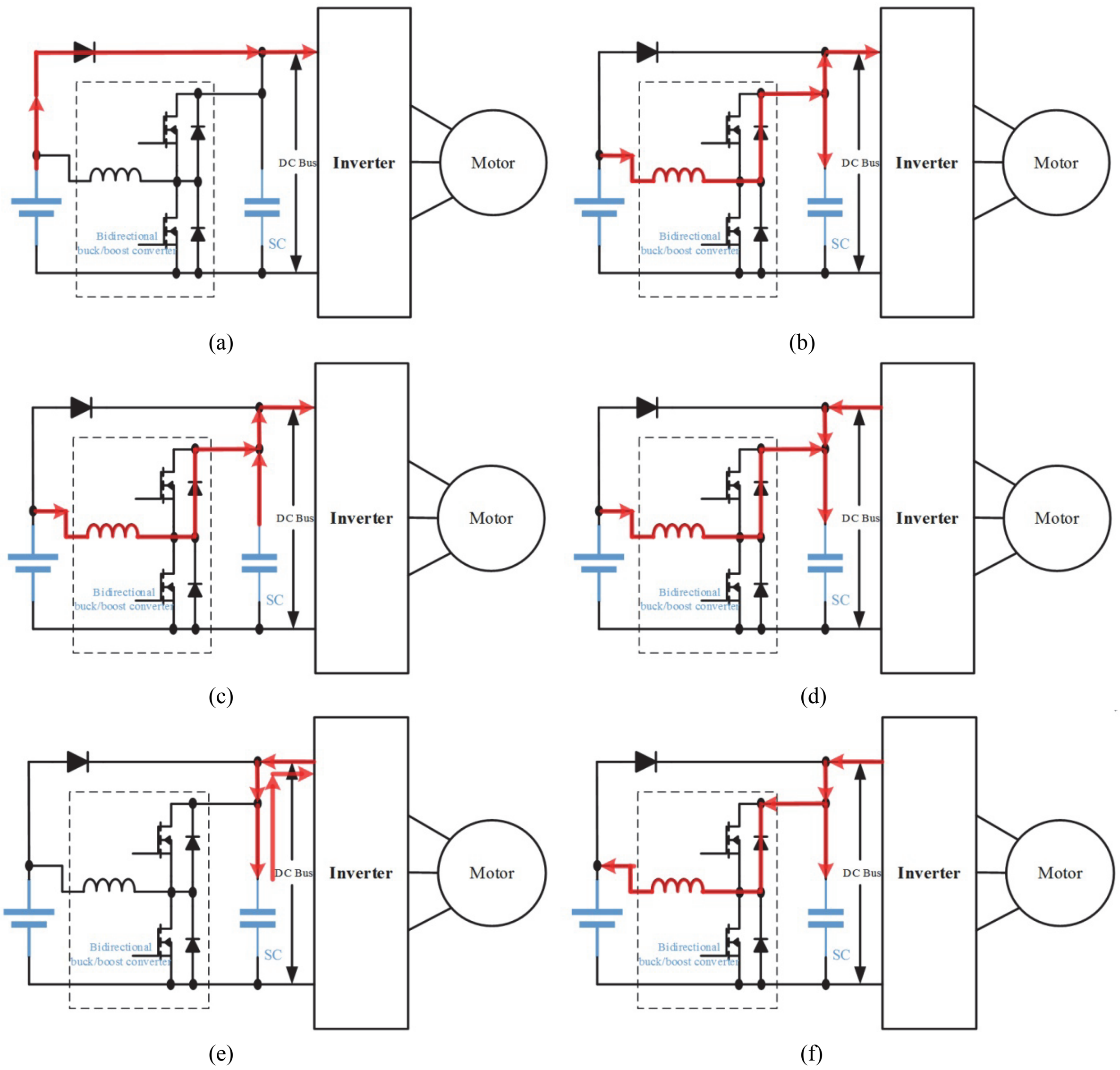

Fig. 5 Operating mode of the proposed hybrid storage system: (a) pure battery powered mode, (b) low voltage powered mode, (c) high load hybrid powered mode, (d) low voltage regenerative braking energy recovery mode, (e) pure supercapacitor powered mode, (f) hybrid regenerative braking energy recovery mode.

3. MODELING OF THE HYBRID STORAGE SYSTEM

The battery module consists of 18Ah lithium batteries in 16 series. If the maximum output current of the battery module is limited to 1C, it can provide a maximum power of 900 W. The detailed specifications are tabulated in Table 1 below.

Table 1 Specification of the battery module

Battery type	$LiFePO_4$
Cell voltage	3 ~ 3.6V_{dc}
Capacity	18Ah
Series	16

The supercapacitor module is connected in parallel with the DC bus in the hybrid energy storage system. Its main function is to absorb the transient power of the load and stabilize the DC bus voltage. In this system, the DC bus voltage ranges from 50 V to 70 V. In order to not only stabilize the supercapacitor module voltage within a safe range but also make the supercapacitor module have the same energy storage range during charging and discharging, the supercapacitor module voltage was used as a parameter V_{sc_ref} to maintain the stability of the system. This supercapacitor module also has a voltage range of 50 ~ 70 V. The energy stored in the supercapacitor module needs to be kept within the controllable energy range of the system. The energy stored in this voltage range is expressed by (1) and reflected in the system stability by half of the controllable energy of the system. The threshold voltage value V_{sc_ref} can be expressed as (2), and the system stable voltage is set to V_{sc_ref} = 61 V.

$$E_{sc\_\max} = \frac{C_{sc}}{2}(V_{sc\_\max}^2 - V_{sc\_\min}^2) \quad (1)$$

$$V_{sc\_ref} = \sqrt{\frac{(V_{sc\_\max}^2 + V_{sc\_\min}^2)}{2}} = \sqrt{\frac{(70^2 + 50^2)}{2}} = 60.83 \approx 61(V) \quad (2)$$

The supercapacitor module voltage ranges from the threshold voltage V_{sc_ref} = 61V to the minimum voltage V_{sc_min} = 50 V. The controllable energy in this voltage range will be sufficient to provide the energy required for a sudden change in the load. From the UDDS operating conditions given in Fig. 4, the section from t = 187 s to t = 205 s is the one with the largest load demand. Therefore, the load energy required in this section is used to determine the capacity of the supercapacitor module. The load power required in this section is accumulated to obtain the total required energy E_{load} = 14627J. The total energy in this interval will be provided by the supercapacitor module and bidirectional converter, and the supercapacitor module voltage will be stabilized at more than 50 V. It is assumed that the bidirectional converter provides half of the maximum power to the load in this interval, that is, a constant power output of 250 W. Therefore, at t = 187s to t = 205s, the bidirectional converter provides energy E_{cov} = 4750J to the load, and the supercapacitor module have to be responsible for providing the remaining energy, $E_{sc} > E_{load} - E_{conv}$ = 9877J, as shown in (3), and we can get (4) after rewriting (3). The entire supercapacitor module requires at least 16.179F. There are 32 supercapacitors of 300F in series, and two strings are connected in parallel to achieve 18.75F. The detailed specifications of the supercapacitor are shown in Table 2.

$$E_{sc} = \frac{C_{sc}}{2}(V_{sc\_ref}^2 - V_{sc\_\min}^2) > 9877 \quad (3)$$

$$C_{sc} > \frac{2 \times 9877}{(V_{sc\_ref}^2 - V_{sc\_\min}^2)} = \frac{2 \times 9877}{(61^2 - 50^2)} = 16.179F \quad (4)$$

Table 2 Specification of the supercapacitor module

Cell voltage	1.56 ~ 2.2V_{dc}
Cell capacity	300F
Series	32
Parallel	2

In order to obtain accurate simulation results to compare with the actual measured results, this research study is to substitute the actual component parameters for the built-in model of MATLAB to facilitate the simulation. Figure 6 shows the battery charge/discharge characteristic curve based on the built-in model. Figures 7 and 8 are equivalent circuit models of supercapacitor and bidirectional converter equivalent circuit models established by MATLAB/Simulink, respectively. Fig. 9 illustrates a complete modeling of the proposed hybrid energy storage system.

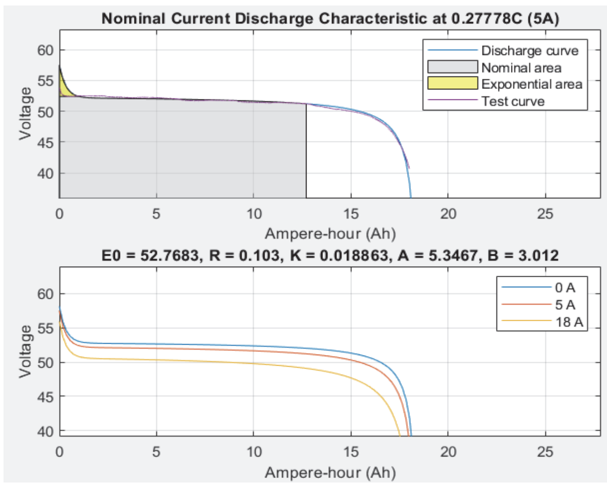

Fig. 6 Charge/Discharge characteristics of the battery module.

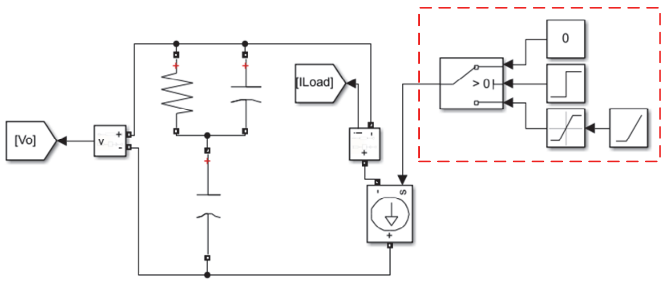

Fig. 7 Equivalent circuit modeling of the supercapacitor module.

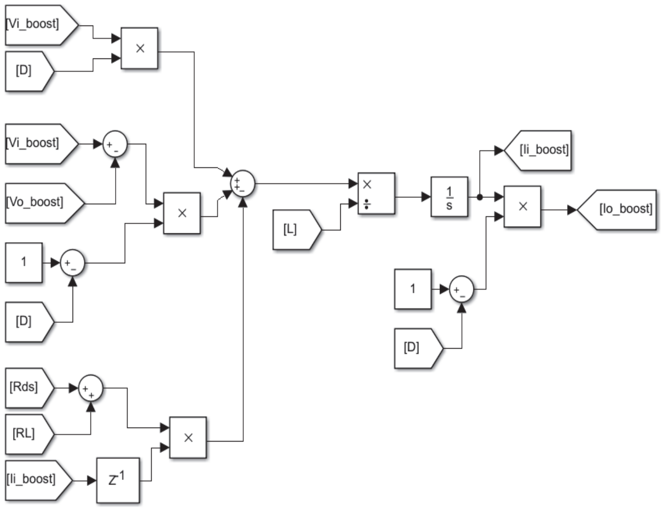

Fig. 8 Modeling of the bidirectional converter by Simulink.

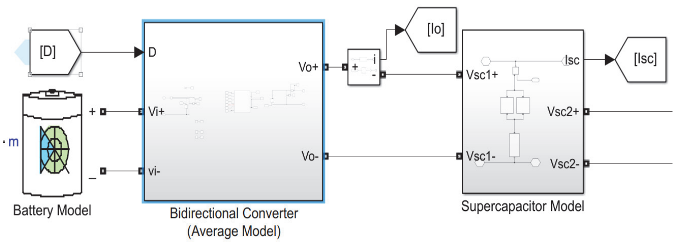

Fig. 9 Modeling of the hybrid storage system by MATLAB/Simulink.

4. SIMULATION AND ENERGY MANAGEMENT STRATEGY

In this paper, a rule-based strategy and a supercapacitor voltage hysteresis control were utilized to implement an energy management to improve the energy utilization rate and reduce the energy loss caused by the energy transfer between each other. Fig. 10 is a schematic diagram of the proposed energy management strategy, with a single voltage and current feedback, a voltage digital filter, a power digital filter, a rule-based strategy, a hysteresis control strategy, and a current loop PI controller. Among them, the supercapacitor module voltage is a feedback parameter used to estimate the actual load power P_{dem}, and then the estimated load power P_{dem} is distributed to the load power through the digital filter 2. So, the high frequency part of the load power is dropped. The obtained load average power P_{ave} is used as the power command of the bidirectional converter. Secondly, as can be seen from Fig. 10, the input signals of the rule-based strategy and the hysteresis control strategy refer to the average load power P_{ave} and the supercapacitor module voltage V_{sc} respectively. According to the input signals, the system operating mode can be determined. Figures 11 and 12 clearly show the flowchart of the proposed load power estimation and schematic diagram of the proposed rule-based control strategy, respectively.

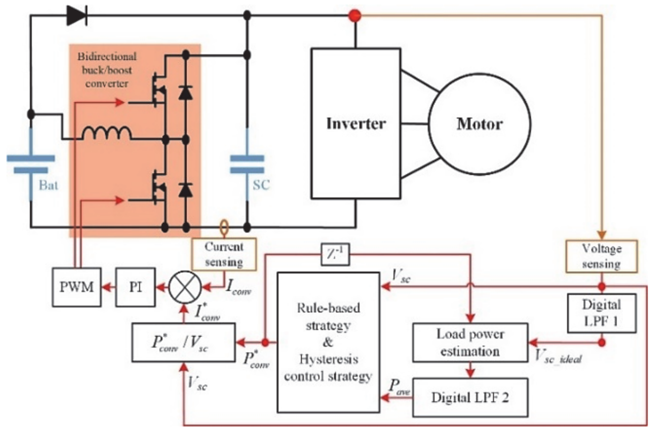

Fig. 10 Schematic diagram of the proposed energy management strategy.

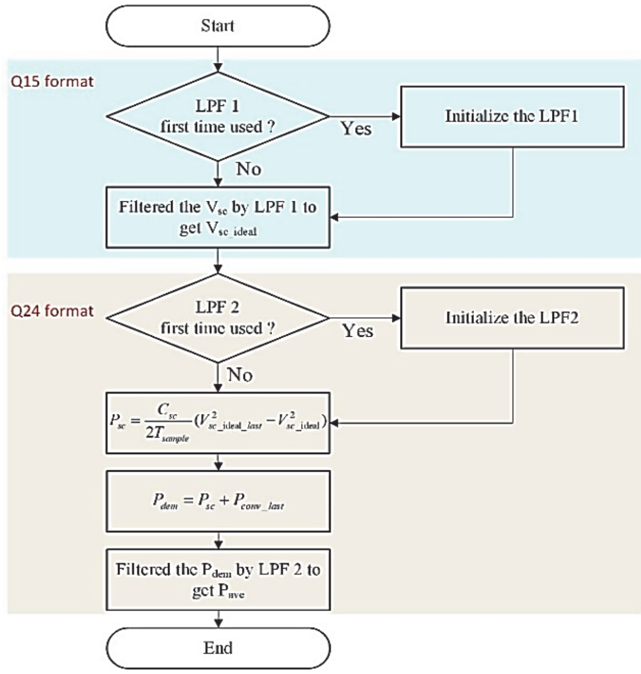

Fig. 11 Flowchart of the load power estimation.

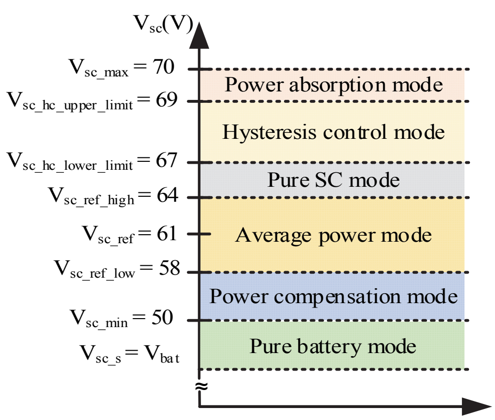

Fig. 12 Schematic diagram of the proposed Rule-based control strategy.

To better implement the proposed energy management for the hybrid energy storage system, we integrated the hysteresis control strategy with the rule-based control strategy to achieve power splitting. Figures 13-15 presents the characteristic curve of the proposed hysteresis control strategy, the flowchart of the proposed Rule-based and hysteresis control strategy, and the complete flowchart of the proposed hybrid storage system control strategy respectively.

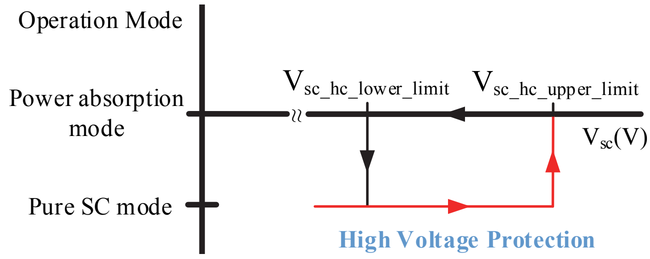

Fig. 13 Characteristic curve of the proposed hysteresis control strategy.

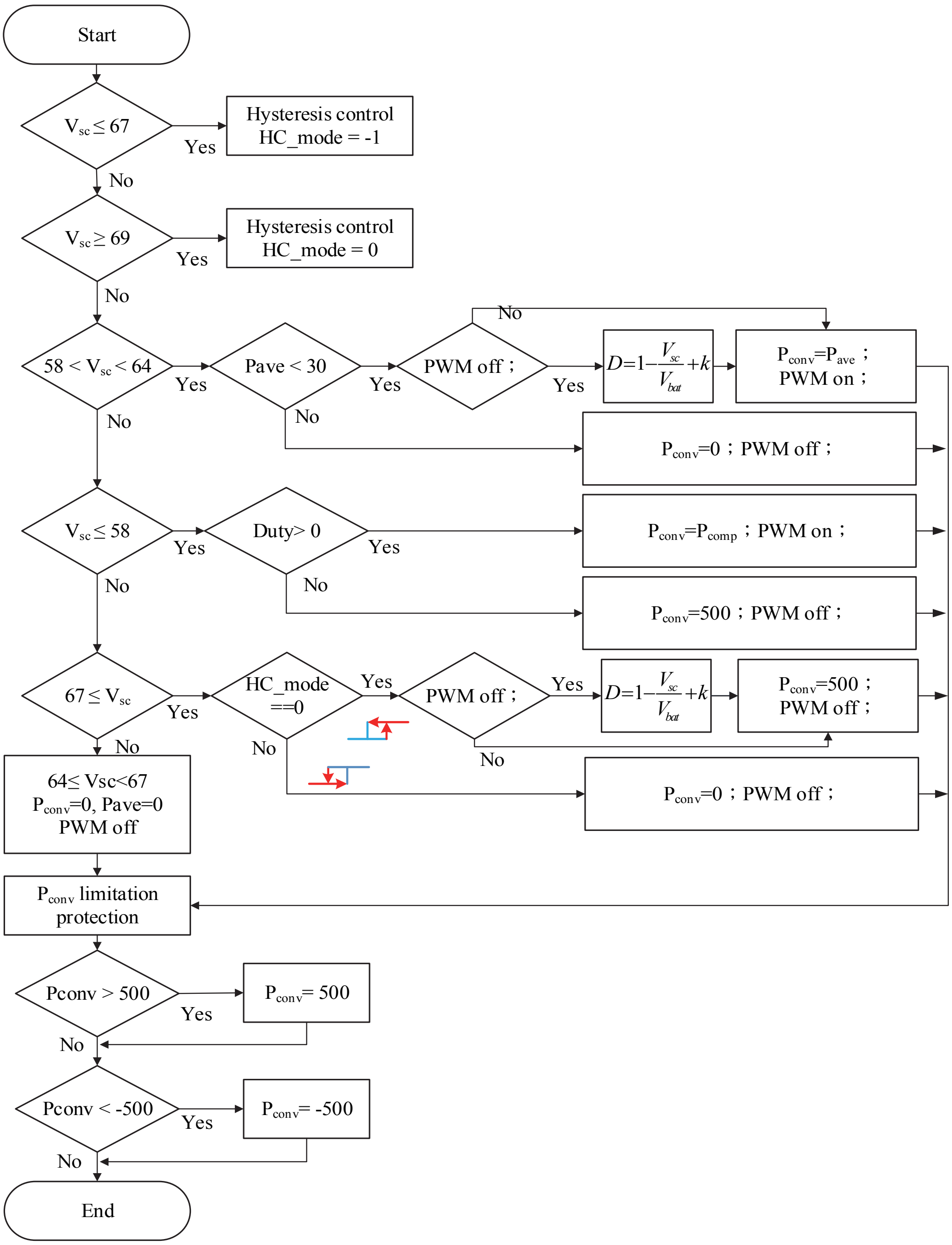

Fig. 14 Flowchart of the proposed Rule-based and hysteresis control strategy.

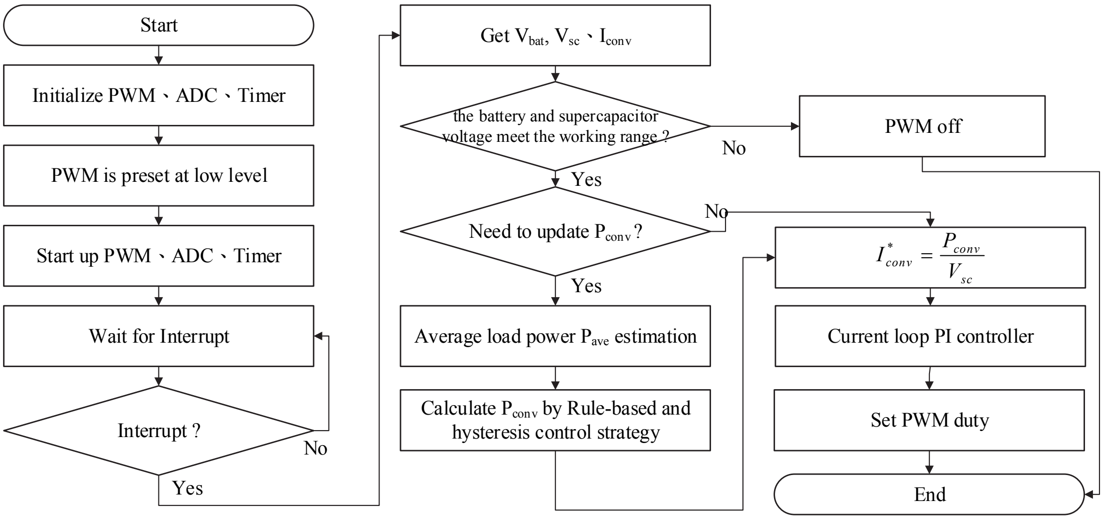

Fig. 15 Flowchart of the proposed hybrid storage system control strategy.

5. EXPERIMENTAL RESULTS

Figure 16 depicts the photograph of the bidirectional converter in the hybrid energy storage system, which integrates the battery module with supercapacitor module to form a hybrid energy storage system. In order to verify the proposed power estimation method and the energy management strategy of the hybrid storage system, a programmable electronic load and a DC power source were used to form a dynamic load with bidirectional control of power, as provided in Fig. 17. The experiment setup of the proposed hybrid storage system is shown as Fig. 18.

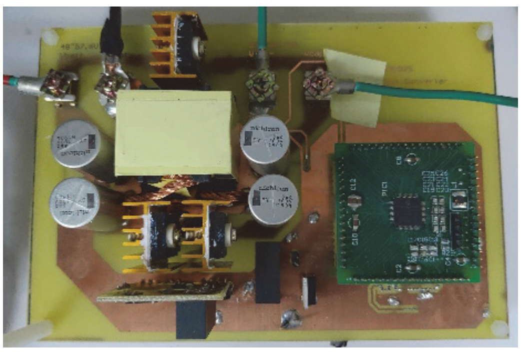

Fig. 16 Photo of the bidirectional converter in the hybrid storage system.

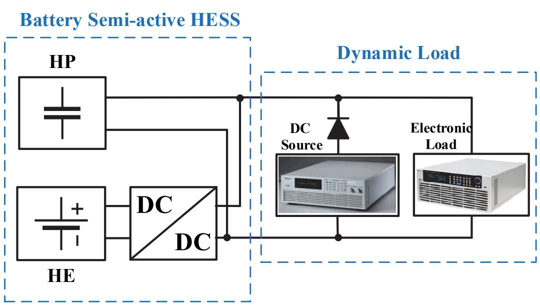

Fig. 17 Block diagram of the test platform for dynamic load test.

This experimental process was to control the electronic load and power supply through the computer to realize the bidirectional dynamic load so as to better achieve the actual load of electric vehicles. The key waveforms measured are presented in Fig. 19. Finally, the measured results were compared with the simulated results, as shown in Fig. 20. The simulated results agree closely with the measured results.

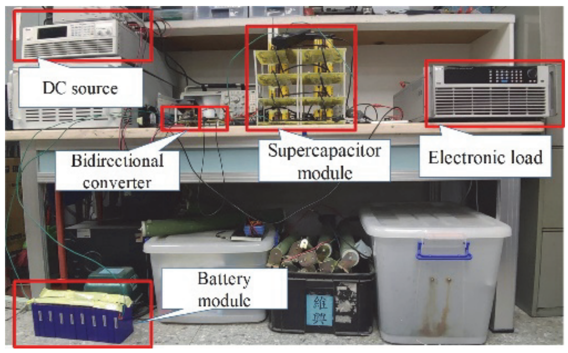

Fig. 18 Experiment setup of the proposed hybrid energy storage system.

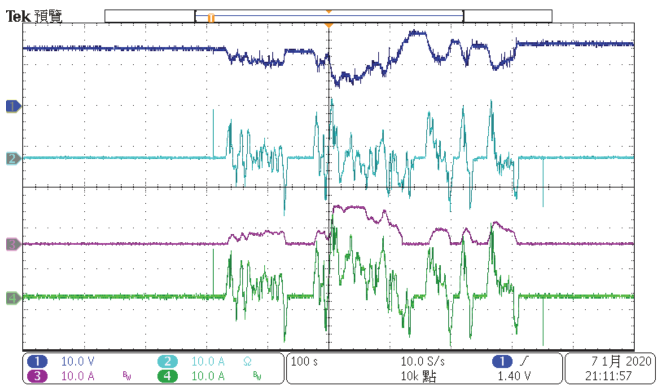

Fig. 19 The measured waveforms of the proposed hybrid storage system. (CH 1: V_{sc}; CH 2: I_{sc}; CH 3: I_{conv}; CH 4: I_{load})

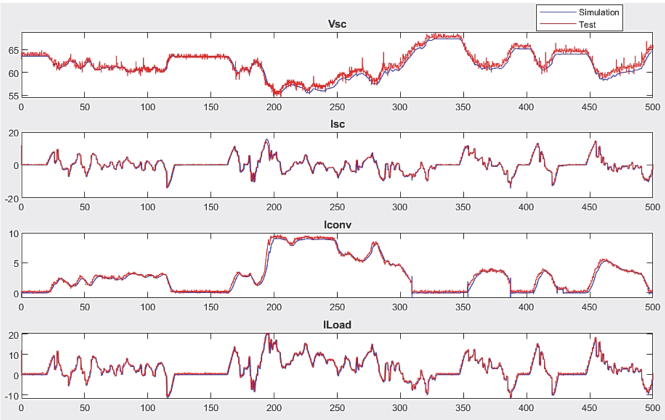

Fig. 20 A comparison between the simulated and measured results. (CH 1: V_{sc}; CH 2: I_{sc}; CH 3: I_{conv}; CH 4: I_{load})

6. CONCLUSION

In this research article, a hybrid energy storage system for electric vehicles was implemented based on the UDDS power curve. Secondly, a battery module and a supercapacitor module with a bidirectional converter was integrated with the proposed hybrid energy storage and connected to a DC bus. Therefore, the battery module could achieve voltage matching through the voltage regulation function of the bidirectional converter. Also, regarding the proposed hybrid energy storage system, the battery module is mainly used to provide the average power required by the load. Therefore, this might suggest that the rated power of the bidirectional converter only needs to be designed to the average load power specification, which can reduce the size and weight of the bidirectional converter. Furthermore, the modeling of the hybrid energy storage system is completed, and the power estimation method is used to obtain the average load power in the control strategy. Then, the energy management strategy should be conducted through the rule-based strategy and the hysteresis control strategy and established by MATLAB closed-loop simulation. Finally, a set of hybrid energy storage system and its test platform were established, and the measurement results were found to be consistent with the simulation results, which can effectively reduce not only the instantaneous high-power pulsed load on the battery module but also the energy transmission losses caused by the trace impedance. This part of the results suggests the great reduction of the battery current stress, which can significantly extend the battery lifespan.

ACKNOWLEDGMENTS

This work was sponsored by the Ministry of Science and Technology, Taiwan, R.O.C., Project number: MOST 106-2221-E-011-094-MY3. This work was also financially supported by the Taiwan Building Technology Center from The Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education in Taiwan.

REFERENCES

Breucker, S.D., Engelen, K., D'hulst, R., and Driesen, J. (2013). "Impact of current ripple on Li-ion battery ageing." *EVS27*, 17-20.

Cao, J. and Emadi, A. (2012). "A new Battery/UltraCapacitor hybrid energy storage system for electric, hybrid, and Plug-in hybrid electric vehicles." *IEEE Trans. on Power Elect*, **27**(2), 122-132.

Dusmez, S., Hasanzadeh, A., and Khaligh, A. (2015). "Comparative analysis of bidirectional Three-level DC–DC converter for automotive applications." *IEEE Trans. on Ind. Elect*, **62**(5), 3305-3315.

Ibanez, F.M., Florez, A.M.B., Gutiérrez, S., and Martín, J. (2019). "Extending the autonomy of a battery for electric motorcycles." *IEEE Trans. on Veh. Tech*, **68**(4), 3294-3305.

Jacobs, I.S. and Bean, C.P. (1963). "Fine particles, thin films and exchange anisotropy." *in Magnetism, vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic*, 271-350.

Kouchachvili, L., Yaïci, W., and Entchev, E. (2018). "Hybrid battery/supercapacitor energy storage system for the electric vehicles." *Journal of Power Sources*, **374**, 237-248.

Kuperman, A., Aharon, I., Malki, S., and Kara, A. (2013). "Design of a aemiactive Battery-Ultracapacitor hybrid energy source." *IEEE Trans. on Power Elect*, **28**(2), 806-815.

Peng, F. Z., Li, H., Su, G.-J., and Lawler, J. S. (2004). "A new ZVS bidirectional DC–DC converter for fuel cell and battery application." *IEEE Trans. on Power Elect*, **19**(2), 54-65.

Uddin, K., Moore, A.D., Barai, A., and Marco, J. (2016). "The effects of high frequency current ripple on electric vehicle battery performance." *Applied Energy*, **178**, 142-154.

Wang, B., Xu, J., Cao, B., and Zhou, X. (2015). "A novel multimode hybrid energy storage system and its energy management strategy for electric vehicles." *Journal of Power Sources*, **281**, 432-443.

Wang, B., Xu, J., Xu, D., and Yan, Z. (2017). "Implementation of an estimator-based adaptive sliding mode control strategy for a boost converter based battery/supercapacitor hybrid energy storage system in electric vehicles." *Energy Conv. and Manag*, **151**, 562-572.

Wang, B., Xu, J., Wai, R., and Cao, B. (2017). "Adaptive Sliding-Mode with hysteresis control strategy for simple multimode hybrid energy storage system in electric vehicles." *IEEE Trans. on Ind. Elect*, **64**(2), 1404-1414.