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Battery-Supercapacitor Current Control Using Fuzzy Supervisory with PI Controller for Electric Vehicle Application

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ABSTRACT

The configuration of the battery-supercapacitor as a hybrid power source (HPS) is one solution to overcome the limitations of battery life, such as in an electric vehicle. To achieve battery energy savings when a supercapacitor is added, a control scheme is needed. This paper proposes a battery-supercapacitor current sharing control scheme using Fuzzy Supervisory Control (FSC). The FSC is designed to determine how much current of the battery and supercapacitor need to discharge based on the current requirement of the load. The output of the FSC will produce a reference current which is then controlled in the main closed-loop control using a Proportional-Integral (PI) controller. The control signal in the form of a duty cycle is then used to regulate the battery-supercapacitor current through a DC/DC converter. This control scheme is tested using a resistive load change scenario both simulation and experimental. The results show that the battery-supercapacitor current can be controlled according to the loading conditions.

KEYWORDS

Battery-supercapacitor
Current control
Fuzzy supervisory
Control
PI Controller
Electric vehicle

INTRODUCTION

The increasing number of motorized vehicles will have an impact on the level of air pollution. This situation occurs due to the increasing use of conventional fossil fuels [1]. Currently, an electric vehicle has been present and developed to overcome this problem. A vehicle with an electric energy source plays a major role in replacing conventional transportation because of its environmental-friendly characteristic. However, one of the problems in an electric vehicle that is still being researched is the limited use of electrical energy used, in this case, the battery. Batteries have some limitations such as low power, long charging time, and limited lifecycle [2]. To overcome this problem, one way that can be taken is to add additional sources of electrical energy such as supercapacitor. The supercapacitor has large power characteristics so the use of battery-supercapacitor in electric vehicles can be used as an alternative energy source in a form of hybrid power sources (HPS). HPS combines two or more sources of electrical energy with different characteristics and covers each other [3]. The supercapacitor has advantages when compared to the battery where it has faster charging and discharging times.

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Based on the above background, the battery-supercapacitor configuration can be an alternative power source solution for an electric vehicle. This study aims to design a battery-supercapacitor current sharing strategy that allows for battery power savings.

LITERATURE REVIEW

Various studies related to HPS control schemes such as batteries-supercapacitors have been developed by many researchers. Z. Cabrane, et al [4] researched energy management strategies with a DC bus voltage regulation approach in photovoltaic applications. The combination of battery and supercapacitor shows the effectiveness of the proposed strategy to maintain the DC bus voltage at 400 V and can maintain the SoC of the battery and supercapacitor at a higher level. Similar research on HPS was also conducted by researcher R. Prambudi, et al [5]. Researchers conducted a simulation of battery and supercapacitor hybrid energy storage as a smoothing output power in wind turbine applications. Taking into account the SoC of each energy storage, the proposed control scheme can keep the battery-supercapacitor SoC at the desired level, which is between 25% to 95%. A different study was conducted by M. Zand, et al [6] who designed an energy management scheme in a hybrid power generation system with a combination of fuel cells (FC), batteries, and supercapacitors. In this system, FC is the main source while batteries and supercapacitors are used as additional energy sources. With adaptive fuzzy control and Social Spider Algorithm (SSA), the simulation results verify that the proposed method provides better performance than the Power Tracking Control (PTC) system.

HPS research that utilizes electric vehicles has also been carried out using various methods/algorithms. The research of K. Ye and P. Li [7] carried out control optimization for electric vehicles with steady-state power from the power divided as the ideal battery output power. The control method used is Proportional Integral Derivative (PID) control with Particle Swarm Optimization (PSO) algorithm to build a power difference control structure. M. C. Joshi and S. Samanta [8] conducted research on energy management studies with frequency division algorithms for HPS in electric vehicles. The implementation is carried out on Arduino Mega 2560-based HPS with an improved algorithm to share battery current loop errors during transients with faster supercapacitor current loops. M. R. Hans, et al [9] conducted a study on HPS in an electric vehicle with Fuzzy Logic Control (FLC). The purpose of this research is to implement an energy management strategy for variations in the required power requirements using MATLAB/Simulink simulations. J. J. Eckert, et al [10] conducted a study on the design of multiple drive trains in electric motors with HPS power separation and two HPS systems, where each source is responsible for each drive train. With Genetic Algorithms and FLC, the proposed dual-HPS configuration can increase the driving range to 145.15 km while also reducing 23.93% of the mass of HESS. A. S. Babu and A. T. Vijayan [11] designed an energy management scheme (EMS) for hybrid electric vehicles by driving the Permanent Magnet Synchronous Motor (PMSM) as a generator. With FLC, the test results show the effectiveness of EMS in increasing acceleration and keeping the battery from discharging well. M. Van Jaarsveld and R. Gouws [12] conducted research on energy management and control systems for HPS battery-supercapacitor using a DC/DC converter. HPS control and topology based on FLC in MATLAB/Simulink simulations show that topology and control strategies are better than passive topologies in reducing peak power impulses on the battery and increasing vehicle range. The use of HPS needs to pay attention to the various loading profiles and scenarios that will be designed. D. R. Brafianto [13] designed an energy management system on a battery and supercapacitor hybrid electric vehicle by applying power-sharing settings based on the designed scenario. Research on HPS on electric vehicles with road contour schemes was carried out by T. Dhia, et al [14] and J. Hu [15]. The use of road contours causes current surges and battery voltage drops which can reduce battery life.

Based on the literature review above, it can be concluded that the use of battery-supercapacitors can be an alternative solution for saving battery power, especially in electric vehicle applications. Fuzzy logic-based control is the most widely used because it has the convenience of designing which is only based on logical rules. In contrast to several previous studies, the focus of this research lies in the application of a battery-supercapacitor FLC scheme in electric vehicles where the control will produce a supercapacitor reference current. This scheme is called Fuzzy Supervisory Control (FSC) because fuzzy logic is used to determine the reference signal. To achieve the battery-supercapacitor reference current generated by the FSC, a Proportional-Integral (PI) controller is added as a current controller which will regulate the switching of the DC/DC converter. Thus, the battery-supercapacitor current can be controlled according to the loading conditions.

RESEARCH METHOD

Battery Model

In this study, we use Lithium-ion battery model as the main power source on the HPS. The Lithium-ion battery circuit can be represented in an electric circuit model which consists of resistors and capacitors as shown in Figure 1 [16].

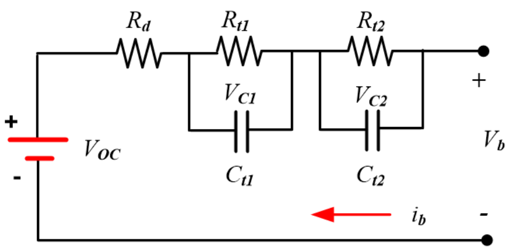


Figure 1. Lithium-ion battery electric model

The battery voltage equation and its dynamic part can be written as follows:

$$V_b(t) = -R_d i_b(t) - V_{C1}(t) - V_{C2}(t) + 2a_1 SOC_n(t) + (2a_1 + 2a_0) \quad (1)$$

$$\frac{dV_{C1}(t)}{dt} = -\frac{1}{R_{t1}C_{t1}} V_{C1}(t) + \frac{1}{C_{t1}} i_b(t) \quad (2)$$

$$\frac{dV_{C2}(t)}{dt} = -\frac{1}{R_{t2}C_{t2}}V_{C2}(t) + \frac{1}{C_{t2}}i_b(t) \tag{3}$$

$$\frac{dSOC_n(t)}{dt} = -\frac{1}{Q_n}i_b(t) \tag{4}$$

with R_d is the inner resistance, a_1 is the battery voltage when the state of charge (SOC) is 100%, a_0 is the battery voltage when the SOC is 0%, R_{t1} is the first terminal resistor, R_{t2} is the second terminal resistor, C_{t1} is the first terminal capacitor, C_{t2} is 2nd terminal capacitor, and Q_n is the capacity of Lithium-ion.

Supercapacitor Model

The supercapacitor can be modeled as a capacitor (C) which is added in series resistance (Rs), series inductance (L), and parallel resistance (Rp) as shown in Figure 2.

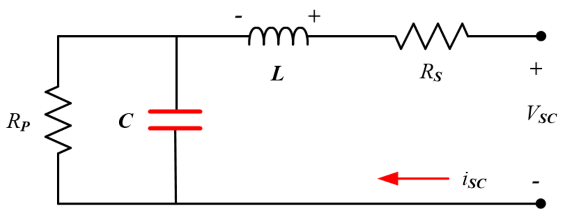


Figure 2. Supercapacitor electric model

The values of C and L depend on each type of supercapacitor construction. Rs is the internal resistance that causes the voltage to drop during charging and discharging. Rp is the resistance that causes self-discharge in the supercapacitor. Based on the electric model circuit above, the supercapacitor voltage equation can be written as follows.

$$V_{SC}(t) = -R_s i_{SC}(t) - L\frac{di_{SC}(t)}{dt} - V_C \tag{4}$$

With V_{SC} is supercapacitor voltage, i_{SC} is supercapacitor current, and V_C is ideal capacitor voltage.

Proposed Control Scheme

Figure 3 shows the proposed control diagram of the battery-supercapacitor. In this block diagram, there is a battery-supercapacitor as HPS, two units of DC/DC converter, and a load profile. We use an active HPS topology that utilizes a DC-DC converter for the battery and supercapacitor. This topology allows for controlling the flow of power from each energy source. As an initial stage and limitation of the research, instead of torsional loads on electric vehicles, the load profile used is resistive loads which are assumed to be loading conditions on electric vehicles. Because in this study, the current response of the battery-supercapacitor will be seen when it is given a load. As it is known that the current has a directly proportional relationship with the torque, but is inversely proportional to the resistance. Thus, a given resistive load can be considered a torsional load in its inverse. FLC is designed as a supervisor control where the output will be used as a reference for the next control. In the next level controller, the PI controller is used to generate a PWM signal which will be used to adjust the DC/DC converter.

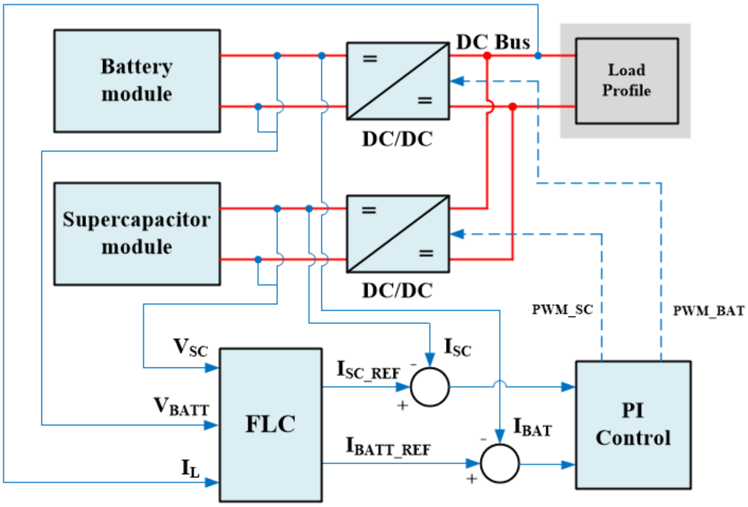


Figure 3. Proposed control scheme

Controller Design

In this study, the FLC topology used is supervisory (FSC). FSC is designed to generate battery-supercapacitor currents as a reference signal to the next controller. The inputs from the controller are supercapacitor voltage (Vsc), battery voltage (Vbatt), and load current (Iload), while the outputs are reference supercapacitor current (Isc_ref) and reference battery current (Ibat_ref). This variable is then created in the form of a membership function as shown in Figure 4 and Figure 5 following.

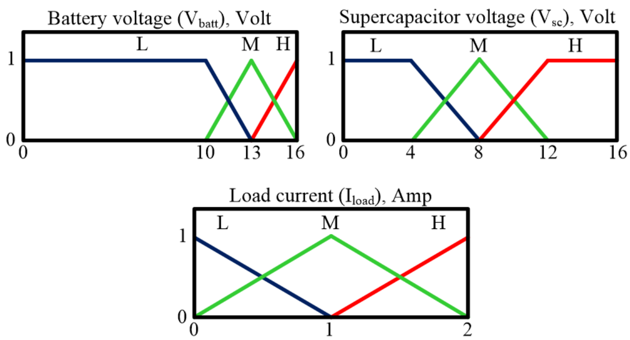


Figure 4. The input membership function

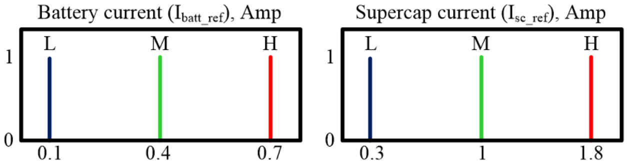


Figure 5. The output membership function

The membership function for each variable is as follows: (1) 0 ≤ Vbatt ≤ 16; (2) 0 ≤ Vsc ≤ 16; (3) 0 ≤ Iload ≤ 2; (4) 0 ≤ Ibatt_ref ≤ 1; and (5) 0 ≤ Isc_ref ≤ 2. The size of this membership function is determined based on the design specifications of the load. The fuzzy logic method used in this research is Takagi-Sugeno-Kang (TSK) where the output is a crisp value that has a degree of membership. The value of the output can be calculated based on:

$$z_{out} = \frac{\sum_{i=1}^{n} w_i z_i}{\sum_{i=1}^{n} w_i} \tag{5}$$

where z_{out} is the firm output value, z_i is the i-th value of the output function, and w_i is the weight of the i-th value of the output function. Battery-supercapacitor HPS control using FSC is carried out based on the following rules:

1. If (Vbatt is Low) and (Vsc is Low) and (Iload is Low), then (Ibat_ref is Low) and (Isc_ref is Low)
2. If (Vbatt is Low) and (Vsc is Low) and (Iload is Medium), then (Ibat_ref is Low) and (Isc_ref is Medium)
3. If (Vbatt is Low) and (Vsc is Low) and (Iload is High), then (Ibat_ref is Medium) and (Isc_ref is High)
4. If (Vbatt is Low) and (Vsc is Medium) and (Iload is Low), then (Ibat_ref is Low) and (Isc_ref is Low)
5. If (Vbatt is Low) and (Vsc is Medium) and (Iload is Medium), then (Ibat_ref is Low) and (Isc_ref is Medium)
6. If (Vbatt is Low) and (Vsc is Medium) and (Iload is High), then (Ibat_ref is Medium) and (Isc_ref is High)
7. If (Vbatt is Low) and (Vsc is High) and (Iload is Low), then (Ibat_ref is Low) and (Isc_ref is Low)
8. If (Vbatt is Low) and (Vsc is High) and (Iload is Medium), then (Ibat_ref is Low) and (Isc_ref is Medium)
9. If (Vbatt is Low) and (Vsc is High) and (Iload is High), then (Ibat_ref is Low) and (Isc_ref is High)
10. If (Vbatt is Medium) and (Vsc is Low) and (Iload is Low), then (Ibat_ref is Low) and (Isc_ref is Low)
11. If (Vbatt is Medium) and (Vsc is Low) and (Iload is Medium), then (Ibat_ref is Medium) and (Isc_ref is Medium)
12. If (Vbatt is Medium) and (Vsc is Low) and (Iload is High), then (Ibat_ref is High) and (Isc_ref is Medium)
13. If (Vbatt is Medium) and (Vsc is Medium) and (Iload is Low), then (Ibat_ref is Low) and (Isc_ref is Low)
14. If (Vbatt is Medium) and (Vsc is Medium) and (Iload is Medium), then (Ibat_ref is Medium) and (Isc_ref is Medium)
15. If (Vbatt is Medium) and (Vsc is Medium) and (Iload is High), then (Ibat_ref is Medium) and (Isc_ref is High)
16. If (Vbatt is Medium) and (Vsc is High) and (Iload is Low), then (Ibat_ref is Low) and (Isc_ref is Low)
17. If (Vbatt is Medium) and (Vsc is High) and (Iload is Medium), then (Ibat_ref is Medium) and (Isc_ref is Medium)
18. If (Vbatt is Medium) and (Vsc is High) and (Iload is High), then (Ibat_ref is Low) and (Isc_ref is High)
19. If (Vbatt is High) and (Vsc is Low) and (Iload is Low), then (Ibat_ref is Low) and (Isc_ref is Low)
20. If (Vbatt is High) and (Vsc is Low) and (Iload is Medium), then (Ibat_ref is Medium) and (Isc_ref is Medium)
21. If (Vbatt is High) and (Vsc is Low) and (Iload is High), then (Ibat_ref is High) and (Isc_ref is Low)
22. If (Vbatt is High) and (Vsc is Medium) and (Iload is Low), then (Ibat_ref is Low) and (Isc_ref is Low)
23. If (Vbatt is High) and (Vsc is Medium) and (Iload is Medium), then (Ibat_ref is Medium) and (Isc_ref is Medium)

24. If (Vbatt is High) and (Vsc is Medium) and (Iload is High), then (Ibat_ref is High) and (Isc_ref is Medium)
25. If (Vbatt is High) and (Vsc is High) and (Iload is Low), then (Ibat_ref is Low) and (Isc_ref is Low)
26. If (Vbatt is High) and (Vsc is High) and (Iload is Medium), then (Ibat_ref is Medium) and (Isc_ref is Medium)
27. If (Vbatt is High) and (Vsc is High) and (Iload is High), then (Ibat_ref is Low) and (Isc_ref is High)

Based on these rules, it can be seen that if a high load current is required, then the supercapacitor will be prioritized for use as in rules (3), (6), and (9) under conditions of the low battery voltage, rules number (15) and (18) on medium battery voltage, and rule number (27) on high battery voltage.

After obtaining the current reference of the battery-supercapacitor, the PI controller works to control the battery-supercapacitor current based on the following equation.

$$u(t) = Kp.e(t) + Ki\int e(t)\,dt \tag{6}$$

where $u(t)$ is the PI control signal, Kp is the proportional constant, Ki integral constant, and $e(t)$ is the error signal obtained from the difference between the reference signal and the output signal. The PI constants used are Kp = 1.5 and Ki = 2 which are obtained from the trial and error method. The control signal generated from the PI controller is a duty cycle limited by 0 - 0.9 and then converted into a Pulse Width Modulation (PWM) signal to switch the Mosfet on the DC/DC converter as depicted in Figure 6.

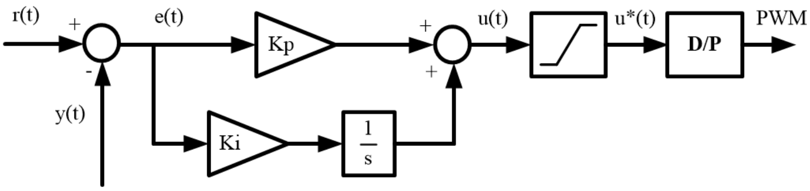


Figure 6. PI controller design

RESULTS AND DISCUSSION

Fuzzy Supervisory System Testing

FSC algorithm testing is done by comparing the design data in the MATLAB simulation through the Fuzzy Logic Toolbox with programming embedded in the Arduino microcontroller. The test was carried out by taking ten random input data consisting of battery voltage (Vbat), supercapacitor voltage (Vsc), and load current (ILoad). The test data are shown in Figure 7.

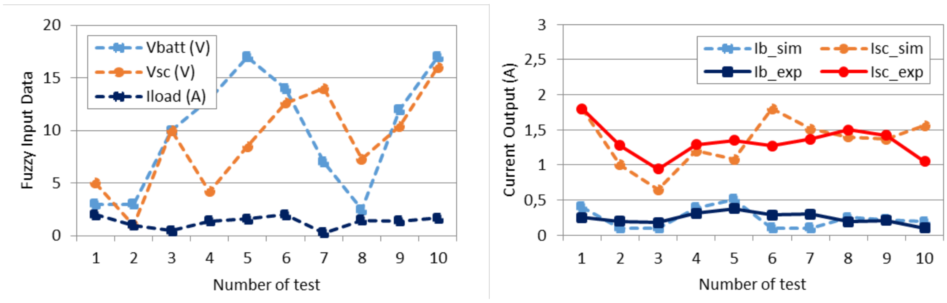


Figure 7. FSC algorithm testing: input data (left) and output data (right)

Based on the results of the tests carried out, it can be concluded that the output of the FSC algorithm between MATLAB simulations and programming (experiments) is almost the same. There is an error in the battery-supercapacitor current output where the average battery current output error is 0.46% and the supercapacitor current output error is 0.25%. This shows that the FSC program that has been created and embedded in the microcontroller is following the results of the design and simulation.

Current Control Simulation Result

Simulations were first carried out to find out the control response in loading conditions. The simulation circuit is made in MATLAB/Simulink as shown in Figure 8 with the detailed subsystem in Figure 9. The simulation parameters used in this study are listed in Table 1. The test is carried out by applying the designed FSC controller and PI controller as a current controller so that the reference current can be tracked.

Table 1. Simulation parameters

Parameter	Value
Battery	Li-ion model 14 V / 3500 mAh
Supercapacitor	35 F / 16 V
DC/DC converter	Boost type, L = 2 mH, C = 100 uF
Sampling time	2.5×10^{-5} s
PI constant	Kp = 1.5, Ki = 2
Solver	ODE 23 (Bogacki-Shampine)

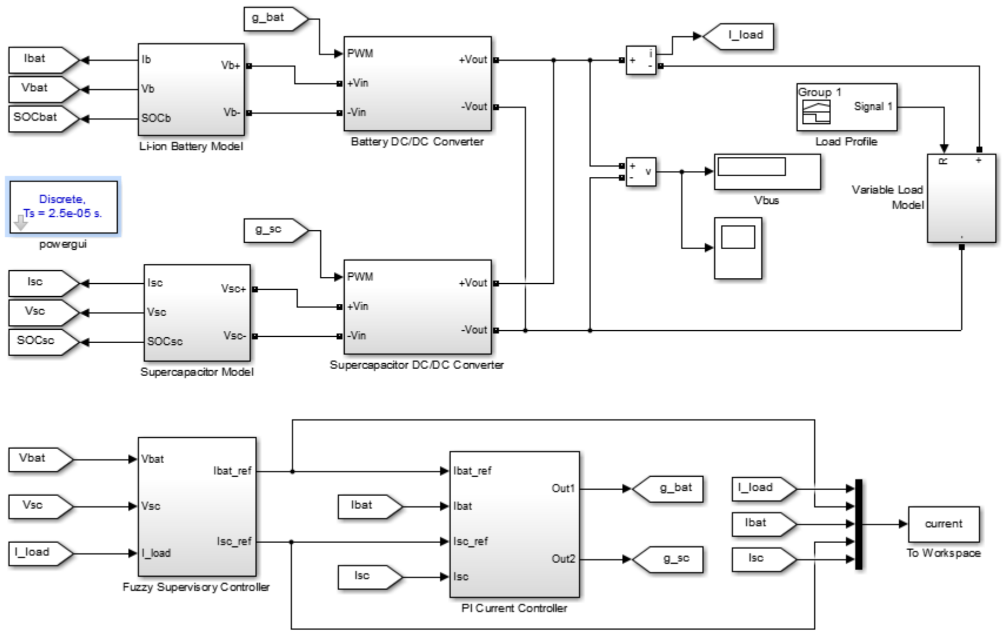
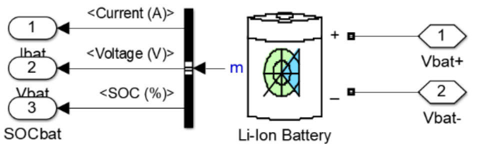
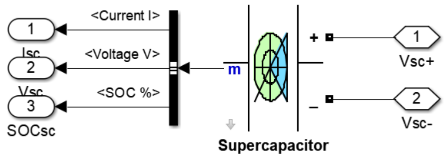


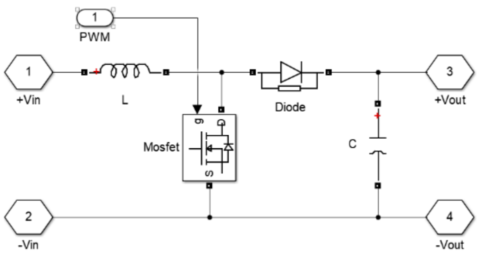
Figure 8. Simulation diagram on MATLAB/Simulink



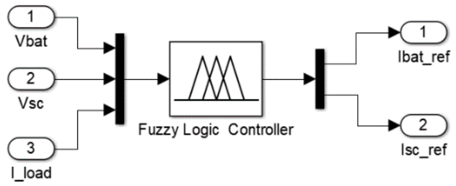
(a) Battery subsystem



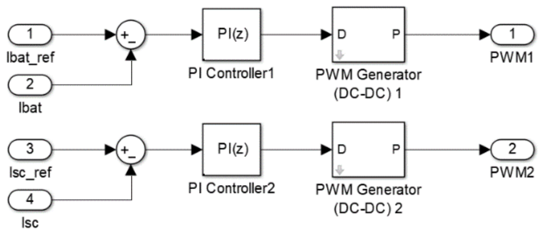
(b) Supercapacitor subsystem



(c) DC/DC boost converter subsystem



(d) Fuzzy Logic Controller subsystem



(e) PI controller subsystem

Figure 9. Detailed subsystem in simulation diagram

The test was carried out in a simulation using a changing load profile as shown in Figure 10. The resistive load changed from 20 Ohms to 12 Ohms, then back to 20 Ohms.

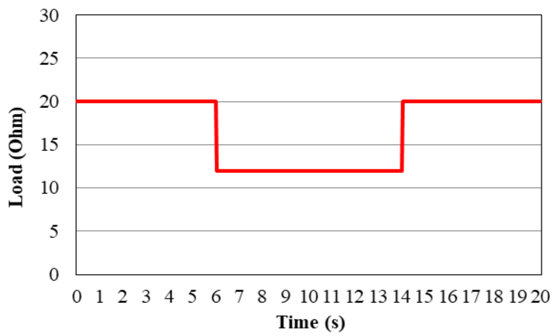


Figure 10. Load profile for system testing

Figure 11 shows the test results in a simulation with a changing load. From the simulation results, it can be seen that the battery and supercapacitor currents can be controlled based on the resulting load currents. When the load is 20 Ohms, the load current is about 1.1 A. Based on this condition, the FSC output in the form of a battery and supercapacitor reference current produced is 0.28 A and 0.82 A. This reference current output is following the rule base that has been made, where the supercapacitor current will always be greater than the battery current when the supercapacitor voltage is available. When the load drops to 12 Ohms, the load current rises to 1.55 A. The battery and supercapacitor reference current outputs also change based on the FSC rule base. The battery current drops to 0.20 A, while the supercapacitor current goes up to 1.33 A. Then, these two reference current outputs are controlled using a PI controller to be achieved. The results show that the battery and supercapacitor reference currents can be traced using the PI controller although there is noise in the current responses. This error value is caused by the switching frequency of the DC/DC converter and can be reduced by recalculating the value of the capacitor capacitance in the DC/DC boost converter circuit.

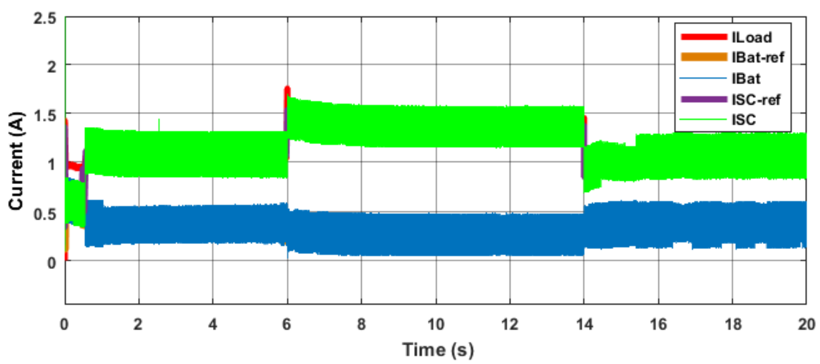


Figure 11. Control performance of battery-supercapacitor current

Figure 12 shows the DC bus voltage output of the battery DC/DC converter and the supercapacitor that flow to the load. It can be seen that the bus voltage decreases as the supercapacitor current increases. The DC bus voltage cannot be stable because it is not used as a control variable. If the DC bus voltage will be stabilized, it can be applied to a DC bus voltage controller using an additional closed-loop DC/DC converter. However, the DC bus voltage only decreases by about 4 V when the current increases. This is acceptable and allowed because naturally in the electrical basic concept, an increase in current can cause a decrease in voltage.

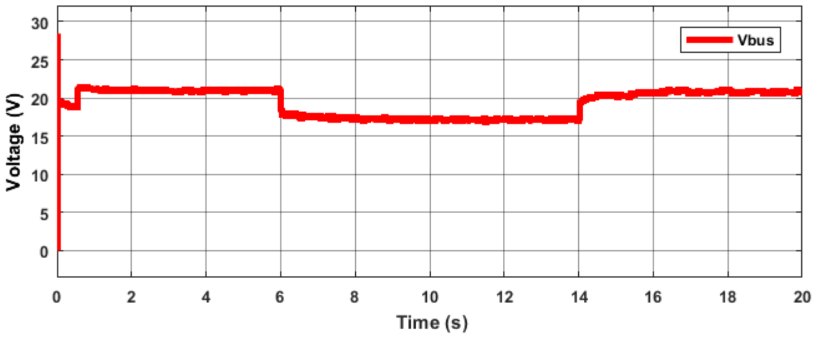


Figure 12. DC bus voltage of battery-supercapacitor

Hardware Experimental Result

Experimental testing is carried out to prove the control results that have been obtained by simulation. The hardware scheme designed for the experiment can be seen in Figure 13. The hardware used consists of a battery module, a supercapacitor module, a DC/DC boost converter, a voltage sensor, a current sensor, an Arduino Uno microcontroller, a dummy load, and a PC with Arduino IDE and MATLAB as a data plotter. Experimental testing was carried out using the same loading conditions and PI controller constants as the simulation. The dummy load is designed with two resistors where R1 is 20 Ohm and R2 is 30 Ohm with a push button as a switch for changing the load value.

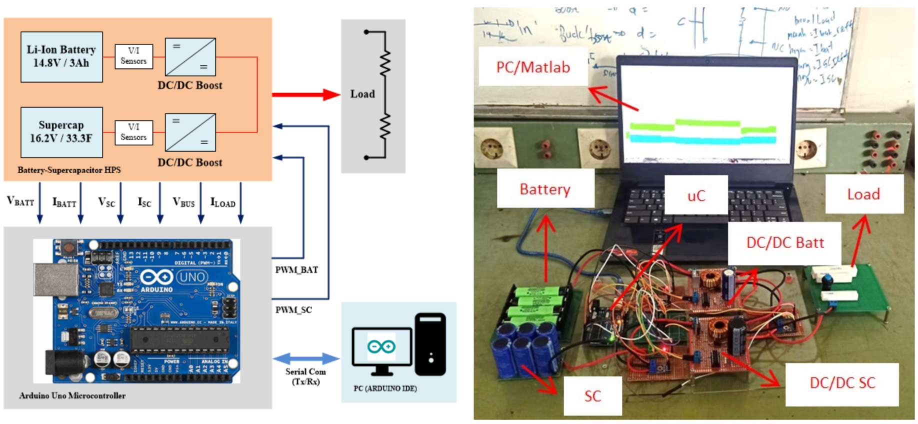


Figure 13. Hardware experimental setup: design (left) and its implementation (right)

In the first condition test, a constant load is given for 6 seconds with a load of R1 of 20 Ohm. In the second condition, the loading value is changed after 8 seconds by pressing the push button on the dummy load so that the load R1 will be connected in parallel with R2 and produce a load value of 12 Ohm. This condition causes a displacement from the first condition of 20 Ohm and then decreases to 12 Ohm. In the third condition 6 seconds later the push button is pressed again so that the load will return to the value of 20 Ohm. Experimental test results can be seen in Figure 14 for the current response and Figure 15 for the DC bus voltage response.

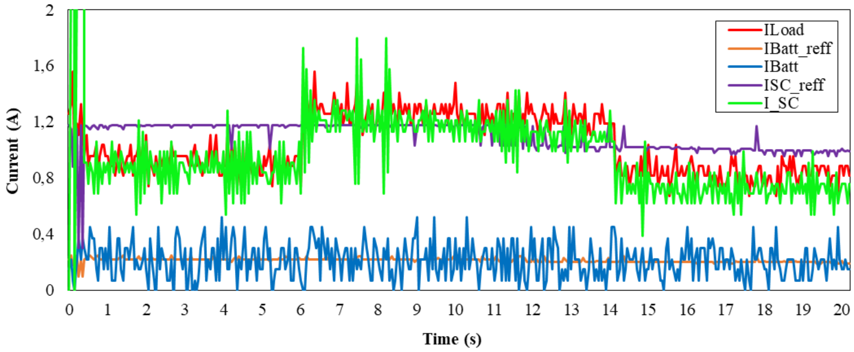


Figure 14. Battery-supercapacitor current control result from experimental testing

Based on the experimental results, it can be seen that in the first condition where the R value is 20 Ohm, the load current will respond quickly followed by the supercapacitor current. The load current will be greater than the supercapacitor current and battery current. In experimental testing, the load value will be in a condition that is inversely proportional to the load current. Experimental testing shows that the current value can be controlled and the results are close to the12imulateon test. This can happen because of the error in reading the graph and the sensor used has low specifications.

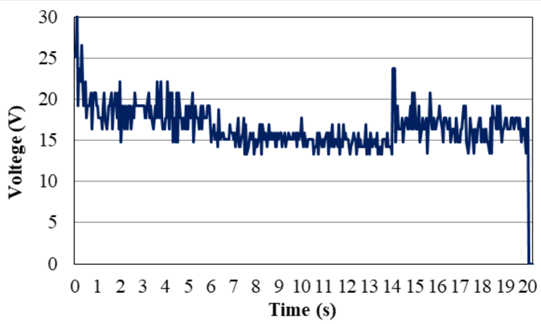


Figure 15. DC bus voltage in experimental testing

The results of the DC bus voltage test in the first condition that on the load R 20 Ohm shows a voltage of about 18 V. In the second condition with the load R changes to 12 Ohm, DC bus voltage produces a voltage of about 15 V. This condition will change along with changes in the load. The DC bus voltage will decrease in direct proportion to the load. In the third condition when the load returns to R 20 Ohm, the voltage will return to a state like the first condition.

Based on the experimental results, it can be concluded that the designed control has succeeded in controlling the battery-supercapacitor current according to the loading conditions. The current and voltage response of the DC bus produced are almost the same as the simulation results, although the measurement noise in the experiment is greater than the simulation results. This happens because of the switching effect of the DC/DC converter, plus the current and voltage sensors used have low specifications.

CONCLUSION

The battery-supercapacitor current control scheme has been successfully designed, simulated, and realized in hardware. The test results both simulation and experiments show that the battery-supercapacitor current can work well together with complementary characteristics. The power density of the supercapacitor can cover the lack of power density in the battery. Supercapacitors can respond to any sudden load changes, so that battery consumption is maintained. FSC and PI controls have worked well in controlling the current of the battery-supercapacitor with the loading scenario that has been designed. Further research can be carried out by controlling the DC bus voltage and testing it with various other loading conditions, one of which is using an electric motor that can simulate the load on an electric vehicle.

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