Supercapacitor Assisted Hybrid Electric Vehicle Powertrain and Power Selection using Fuzzy Rule-Based Algorithm

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***Abstract*—Heavy electric vehicles vary their power demands due to frequently varying loads. The paper proposes an applied fuzzy logic algorithm for the acceleration strategy of supercapacitor assisted electric vehicles, which selects the appropriate power source based on the vehicle power demand. The algorithm can determine the supercapacitor cutoff phase within 200 milliseconds with the developed test vehicle system during the initial vehicle acceleration based on the peak current and current slope. The system reduces battery stress by limiting transient power, improving the hybrid powertrain's longevity and efficiency.**

Keywords—Hybrid electric vehicle, Supercapacitor, Fuzzy logic, Test vehicle

I. Introduction

Electric vehicles have been on the rise in popularity due to growing emissions from petrol road transports [1]. However, the uptake of EVs has been shown problematic in heavier vehicles due to greater power demand, as battery packs increasingly become vulnerable during transient power cycles [2]. The lifespan of a lithium-ion battery is negatively affected by high discharge current and high operating temperatures [3]. Although a specific relationship between peak current and battery life span for batteries has not been established, general research shows reducing peak battery current extends battery life [3]. Vehicles used to transport mass people and goods can have significant and frequent weight differences. Looking at electric trams, the mass of the vehicle can fluctuate from 40 – 60 tons based on the number of passengers [4]. In the process of heavy vehicle electrification, a problem arises. Batteries have relatively low power densities, so they may not meet the power demand for heavier electric vehicles [5]. A common solution to power deprivation is to oversize the battery pack. This method is used in Tesla ® and BYD ® EVs [6]. However, with heavy electric vehicles, the weight and cost penalty increase as the power demand increases, making oversizing inappropriate for such electric vehicles.

Supercapacitor (SC) hybrid powertrains have been used extensively in past literature to reduce battery pack sizes. The primary purpose of the supercapacitor is to lower the current load of the battery during transient power phases [7-9]. Supercapacitors have higher power densities, making them useful to receive high transient power from the motor during regenerative braking [10]. Using the hybrid energy storage system (HESS), benefits to the battery have been shown from the reduction of battery stress and battery longevity improvements [11-13]. However, supercapacitors have low-energy density, which means the discharge must be optimized for minimal time for the state of charge (SoC) [11, 14]. Many past literatures used fuzzy logic algorithms to control the powertrain as no specific model and nonlinear systems are required [15]. In works of [10] [16], fuzzy logic algorithm has estimated SoC, power, and desired supercapacitor current for improved powertrain efficiency. However, much of past works were theoretical. In this paper, a novel current-based fuzzy logic controller is proposed and tested with a realized vehicle system. The powertrain algorithm will select appropriate power sources of the electric vehicle with varying weight loads based on real-time calculation of vehicle peak current and current slope.

The paper is organized as follows: Basis of the powertrain configuration and mathematical models of the vehicle during various drive state is set in Section II. MATLAB simulation of the vehicle profile is analyzed in section III. In Section IV, the membership functions of the fuzzy logic algorithm are described. The empirical evaluation using the test vehicle is shown in section V.

II. System Framework

There are various configuration powertrain configuration designs that employed supercapacitors in past literature. Converter topologies include a system with a low voltage side to the battery pack, low voltage side by the supercapacitor pack. [17], isolated full-bridge [18], and dual half-bridge [19]. It has been shown that half-bridge buck-boost topology shows the most advantage in performance and cost [20]. The configuration design of this paper will rely on the most effective design of a half-bridge buck-boost topology. A simplified design is seen in figure 1.

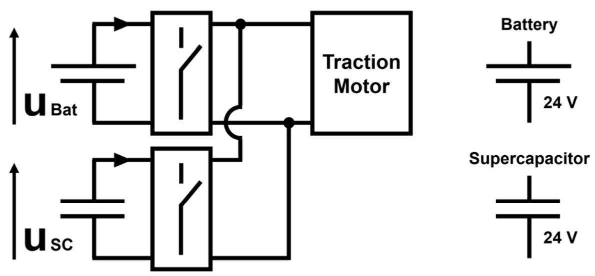

Fig. 1. Hybrid electric vehicle powertrain architecture.

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A. Description of the Studied System

The EV is powered by a lithium-ion battery pack and a supercapacitor module. The system controller determines the appropriate power output based on the power profile of the vehicle. The powertrain is developed to be modular such that all components could be replaced quickly.

A comprehensive configuration of the vehicle powertrain is seen in figure 2. The EV consists of a single motor connected directly to the front and rear differential transmission systems that drive the wheels. The proposed powertrain system allows for the torque motor (TM) to be powered by either a battery pack or the supercapacitor module. The supercapacitor is connected to a DC/DC converter, which allows for constant desired voltage supply to the power management control (PMC).

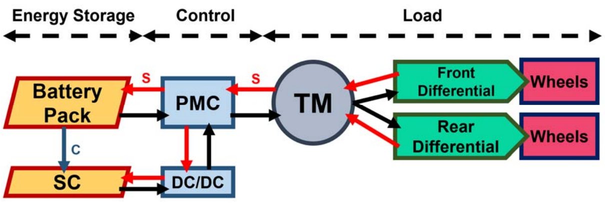

Fig. 2. Power source to motor is indicated by black arrows. Regenerative braking is indicated by red arrows. Battery pack can charge supercapacitor.

B. Power Control Strategy

Based on the power demand from the traction motor, the PMC will select the appropriate power source for the vehicle. Transient power is present during vehicle acceleration and regenerative braking [13]. This means, in most conditions, the supercapacitor module will be activated during vehicle acceleration and regenerative braking. The battery pack will be activated during normal driving conditions.

An example of power demand during different driving phases can be seen with electric trams vehicle speed and power profiles. In a 40 – 60 ton vehicle for a 500 m course in a European urban tramway drive cycle, the acceleration produces a peak power around 600 kW, vehicle coasting (constant speed) lowers the average power to 150, and deceleration produces a peak power of -800 kW. During the acceleration peak and regenerative braking peak, the transient power lasts around 15 s and 10 s, respectively [4].

The PMC will follow a fuzzy rule-based strategy. The rule-based frame is based on the values of demanding current values. The general rule-based control is based on thresholds such that when the current rating is above the exceeding line, the supercapacitor will power the vehicle, which has been used by R. Carter, *et al.* [21]. The implemented algorithm will analyze the driving cycle of the vehicle based on the current rating and determine the source of power. The aim of the power management strategy is for the supercapacitor to power the vehicle during the peak current using minimal discharge time.

Using the fuzzy logic strategy, the battery and the supercapacitor will be activated based on the acceleration/regenerative braking and supercapacitor SoC status. One major drawback of the rule-based algorithm is that variables are usually kept constant. This is problematic in this research as the vehicle load will vary, which will change the power demand from the traction motor. H. Xiao liang, *et al.* [22] has solved the limitation by introducing different power thresholds based on vehicle environments. Similarly, the fuzzy logic used in this paper will introduce different power thresholds based on vehicle power demand.

C. Supercapacitor Activation with SoC

General logic of the powertrain follows, if the supercapacitor has a voltage rating above the minimum operating value, it will be activated during the acceleration of high-power demand. The supercapacitor will handle regenerative braking unless the voltage rating is above the maximum voltage value. If the SoC reaches the lower value or during the normal driving period, the battery will activate to power the vehicle. During this time, the supercapacitor will be charged to the maximum level. This concept is similar to a parallel hybrid on petrol and battery power system. The vehicle cycle is divided into acceleration state, regenerative braking, and coasting state. For the control strategy to function, all power source requirements for driving phases are seen in equation 1.

$$P_{battery} + P_{SC} = P_{acceleration} + P_{vehicle} \quad (1)$$

During coastal drive, the average vehicle power is in the range of average power consumption as power peaks are minimal. As a result, the supercapacitor is not in use as the battery can cover the traction load power. This means $P_{acceleration}$ and P_{SC} are null. The battery pack covers the power, which is seen with equation 2.

$$P_{battery} = P_{vehicle} \quad (2)$$

During acceleration state, the power demand from the vehicle is high. This means the supercapacitor will be used to power the vehicle during acceleration unless the supercapacitor voltage is below its minimal threshold value. This is seen with equation 3.

$$P_{SC} = P_{acceleration} + P_{vehicle}, \ \forall V_{SC} \geqslant V_{SC\,Min} \quad (3)$$

During regenerative braking state, the supercapacitor will receive all power from the braking. The supercapacitor will handle regenerative braking unless the supercapacitor voltage is above its maximal threshold value. The power profile is seen with equation 4.

$$P_{vehicle} = P_{SC}, \ \forall V_{SC} \leqslant V_{SC\,Max} \quad (4)$$

III. Computational Simulation

The algorithm and the paper will focus on vehicle acceleration from this point because the regenerative braking method is simple: power from the motor goes to the supercapacitor based on the supercapacitor SoC status. Also, comprehensive SoC status-based concepts have already been well established. However, because the powertrain in this research deals with vehicles with varying weight loads, the power and current profiles are different for different load weights. Therefore, the algorithm cannot rely on the same power threshold variables used in previous equations during the vehicle acceleration.

MATLAB Simulink simulation of a 20 V electric vehicle powertrain with DC permanent motor was performed to contrast the vehicle speed and power during different load. Vehicle profiles with no additional weight and with additional weight are shown in figure 3.

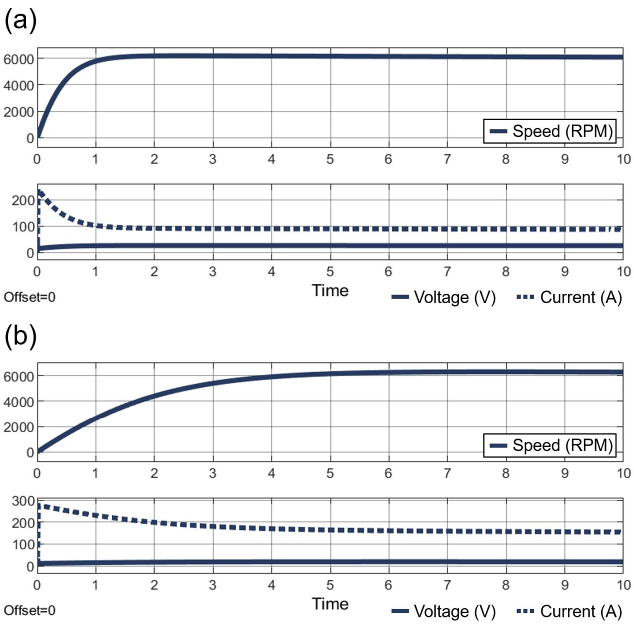

Fig. 3. Top graph shows vehicle profile with no additional weight and bottom graph shows vehicle profile with additional weight.

Graphs show the speed, voltage, and current output from the simulation. A vehicle with no load achieves desiring speed in 1.4 seconds while the vehicle with load takes 5.7 seconds. The peak current and driving current for the heavier vehicle is higher with 285 A and 167 A, respectively. The lighter vehicle shows 247 A and 89 A for peak current and average driving current, respectively.

IV. Fuzzy Logic Algorithm

The vehicle power rating is dynamic due to vehicle weight and must be calculated during acceleration in real time. To predict I_{vehicle}, the fuzzy logic rule-based algorithm is used. Based on the peak current rating and the current slope, the algorithm will determine the current threshold. The general rule of the fuzzy logic is shown below.

1. Heavier vehicles consist of higher peak current.
2. Faster accelerations result in higher peak current.
3. Faster accelerations result in higher current slope.

The reason why current threshold values cannot be determined from the peak current itself is due to the acceleration profile. In comparison, a lighter vehicle with faster acceleration can have the same peak current as a heavy vehicle with lower acceleration, which is seen in figures 3. By introducing the current slope, which looks at the difference in the current value over a certain period of time, the fuzzy logic value will be closer to the average vehicle current rating.

The proposed fuzzy controller is a two-input one-output controller. The first input variable is the peak current in Amps (A). The second input variable is the current slope measured in Amps per millisecond (A/ms). The current slope is the rate in which the current value decreases after founding peak current during acceleration. The algorithm takes the change in the current rating over 200 milliseconds and calculates the current slope. Figure 4 shows the general fuzzy logic architecture.

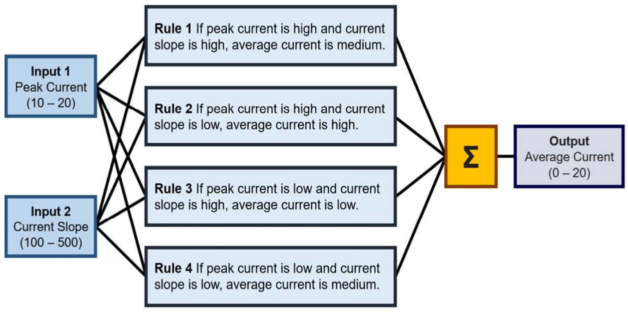

Fig. 4. General architecture of fuzzy logic power controller.

The output of the fuzzy controller is the average current prediction, which will be used with voltage to predict power. The membership functions of inputs and the output of the fuzzy logic algorithm are shown in figure 5.

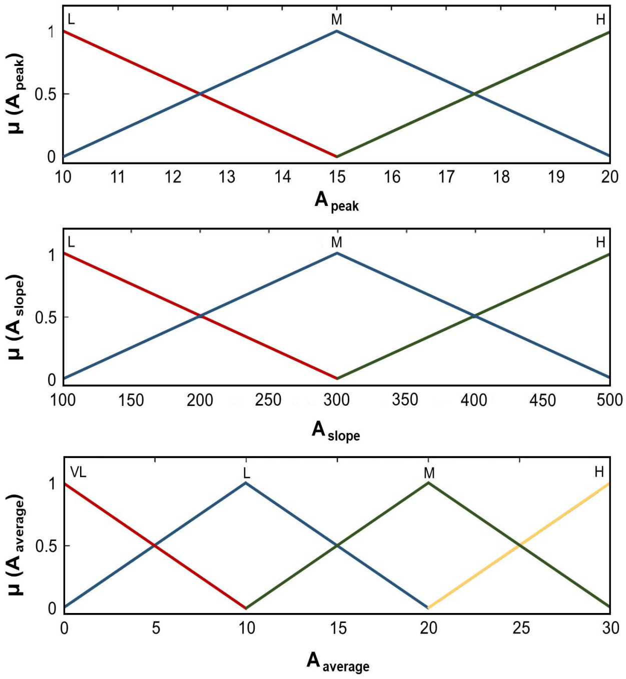

Fig. 5. Fuzzy logic membership functions.

V. Empirical Evaluation

The major goal of the realized vehicle testing was to develop an applied vehicle system that would emulate the computational simulation and perform the fuzzy algorithm with more ease. A fifth scale remote-controlled vehicle was used as the test vehicle. Although power demand values are drastically lower than those of actual electric vehicles, trend with current peak and current slope were similarly emulated, making scaled-vehicle testing useful for deeper analysis of the proposed fuzzy logic controller.

A Control board was developed for testing the power load draw of the vehicle. The basic component of the board consists of a motor controller, battery pack, DC/DC controller, and power sensors. Figure 6 shows the control board and the test vehicle.

A Maxwell 55 F 17 V supercapacitor module was used in the vehicle. Supercapacitor is connected to a buck booster for constant desired voltage to the traction motor. A vehicle without load weighted 20 kg and an additional weight load of 10 kg was added to test the fuzzy logic algorithm with a heavier vehicle. The vehicle consists of a DC permanent magnet motor, which connects axles to all wheels with differentials. Figure 6 shows the image of the control board and the vehicle.

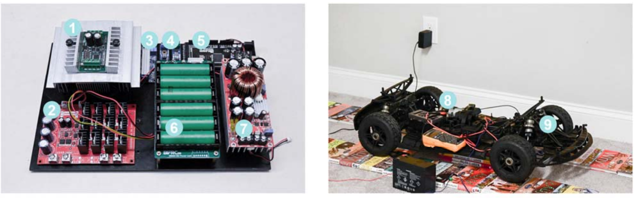

Fig. 6. (1) Motor control board (2) Motor speed controller (3) Buck converter (4) Power sensors (5) Arduino (6) Battery pack (7) DC/DC converter (8) DC permanent magnet motor (9) Differentials.

VI. Results

Figure 7 shows the current profile of the vehicle which will be used for a fuzzy logic algorithm. The vehicle simulated an urban driving cycle where frequent acceleration and deceleration were present. Each vehicle acceleration resulted in current peaks. The vehicle included an Arduino on board, which sensed voltage and current. The first run was with no load and the second run was with an additional load of 10 kg. The vehicle with load achieved higher peak current and vehicle with no load shows a quicker current decrease after the acceleration compares to the vehicle with load, characteristics used for fuzzy algorithm.

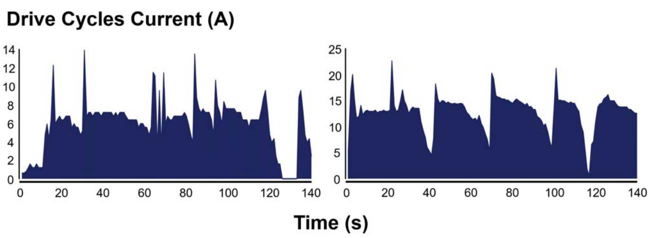

Fig. 7. Top graph is current profile of a 20 kg vehicle. Bottom graph is current profille of a 30 kg vehicle, vehicle with load.

During the vehicle runtime, voltage and current ratings were observed. Figure 8 shows V_{bus} and $V_{supercapacitor}$ during the first 10 seconds of the vehicle acceleration. $V_{supercapacitor}$ was measured between the supercapacitor and the DC/DC converter for actual voltage rating.

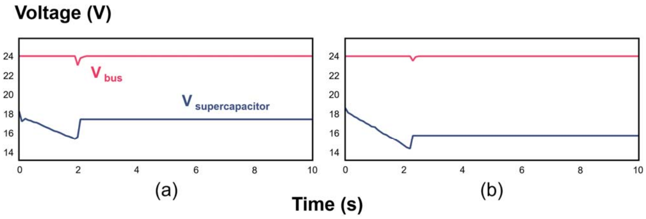

Fig. 8. Voltage graph during acceleration: (a) no load; (b) load

Using a simple Arduino if-else statement, the peak current value was found for each new vehicle acceleration. The applied model with cutoff using fuzzy logic value can be seen in equation 5.

$$I_{vehicle} = I_{SC},\ \forall I_{vehicle} \geqslant I_{\text{fuzzy value}} \tag{5}$$

With equation 5, figure 9 depicts four current profile of the vehicle during the test run. Graphs shows current rating of the traction motor and power selection using fuzzy logic. Peak current is shown at t = 1 s. After the peak current is decided, it takes the current change during 200 milliseconds after the peak current. In graphs, the calculation is performed for 1 to 1.2 seconds. The fuzzy logic output, which is the current threshold value, activates in the powertrain at t = 2 s. The supercapacitor powered the vehicle during peak current stage of the acceleration.

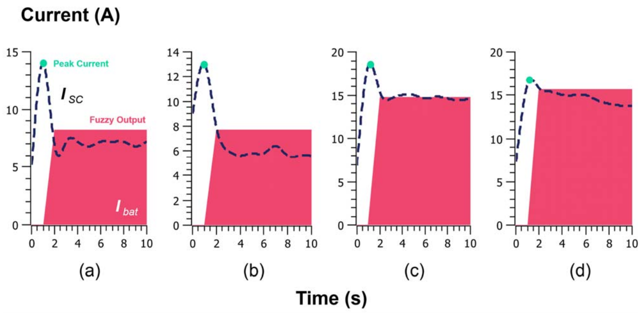

Fig. 9. Current graph during acceleration: (a) (b) no load; (c) (d) load.

An example of the powertrain algorithm will be provided with the graph (a). In this acceleration profile, the peak current was 14.3 A. During the 1 s to 1.2 s, the fuzzy algorithm determined the current slope to be 300 A/ms. Based on two inputs, the fuzzy logic controller resulted in output of 7.94 A. The average current during this run was 6.8 A. The current value is feed through the controller and switches the power source from supercapacitor to battery when the current rating falls below 7.94 A. With this algorithm, the battery pack for the electric vehicle does not need to handle 14.3 A, rather 7.94 A. With multiple testing, the percentage error of the predicted average current value to actual current values were between 6.9% to 18.7%.

VII. Discussion

The fuzzy logic algorithm has allowed the supercapacitor to power the vehicle during peak current and the battery to power the vehicle during the average current. Vehicles with no load showed a greater difference in peak current and average current, which resulted in a lower fuzzy cutoff current value. Vehicles with load showed less current slope, resulting in higher fuzzy cutoff current value. This method decreases the battery load stress, as peak current is handled by the supercapacitor, which has been generally shown to improve battery lifetime. It is also worth noting that vehicle acceleration with the supercapacitor module is faster than a battery-powered acceleration. The fuzzy logic brings the benefit of a relatively simple calculation of the power prediction. However, there are some drawbacks. As seen using six graphs, the error between the prediction and the actual current rating can be high as 18.7%. The error difference can be fixed by introducing more membership functions for better current peak prediction. Although the error showed to be as large as 18.7%, the prediction is always an overestimation, so the transition value between supercapacitor to the battery will always occur, reducing battery peak power in all cases.

VIII. Conclusion

The paper proposed a novel power prediction method of a battery-supercapacitor powertrain using an applied fuzzy logic controller to a test vehicle. During vehicle acceleration, the power prediction is realized using a real-time fuzzy logic system with peak current and current slope calculation, which allows for battery peak current elimination and maximum supercapacitor SoC balance. The presented power control strategy shows the use of supercapacitor during peak current during acceleration and battery during average current ratings.

Results confirmed an effective acceleration strategy only and showed reduced stress to the battery packs. The algorithm allows for electric vehicles with varying loads, such as electric trucks and electric trams, to benefit from supercapacitor hybrid powertrain without requiring pre-entered variables for power control adjustment. Further research and larger prototyping should be performed for usability in commercial electric vehicles.

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