Power management system for a hybrid energy storage electric vehicle using fuzzy logic controller

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ABSTRACT

This research work introduces a power management system for a hybrid energy storage system (PMHESS) configuration for urban electric vehicles utilizing a fuzzy logic controller (FLC). Consequently, the configuration includes two DC/DC interleaved converters that establish a connection between the battery and ultra-capacitors (UCs), thereby ensuring a substantial power capacity. The FLC is adaptable and sturdy, considering information from sources other than the vehicle, such as other vehicles or road infrastructure. The study explores incorporating road topography into the control structure to improve hybrid storage performance. Simulation results show that combining lithium batteries with UCs improves the energy source's performance and reliability. The power management algorithm reduces sudden demands on the battery by considering the slope of the ground. The work proposes energy storage integration for electric vehicles, exploring its benefits through simulations. Overall, the proposed hybrid energy storage system (HESS) demonstrates high efficiency and power for urban electric vehicles. The results are validated using MATLAB/Simulink.

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1. INTRODUCTION

In densely populated urban regions, battery electric vehicles (BEV) are often considered as a potential remedy for the clean environment as huge harm is being caused by conventional automobiles (internal combustion engine (ICE) vehicles) [1]-[3]. Pollutants emitted by ICE vehicles pose a significant threat to both human and environmental health. Furthermore, traffic noise can lead to several health problems, including heart disease, disrupted sleep patterns, and tinnitus [4]-[6]. Some municipalities have implemented restrictions or bans on the use of ICE cars within city limits to combat poor air quality and excessive noise. Electric vehicle (EV) is one of the practical solutions to address the noise and pollution associated with traditional fuels such as gasoline and diesel [7]-[9].

Although BEVs have a shorter range than ICE vehicles, they are well suited for use as city cars, such as for commuters, rental cars, and public transportation vehicles [10]-[12]. BEVs also offer the potential for reduced transportation costs due to their excellent energy efficiency. While BEVs have a lower energy cost per kilometer than ICE cars, the cost of battery replacement is a significant factor that needs to be considered into account [13], [14]. This cost may deter more people from using BEVs, highlighting the need for innovative approaches to extend the useful life of batteries. Warsaw University developed an EV significantly designed for navigating in urban areas. Initially, the vehicle is available for rent based on the price and durability factors [15], [16].

To drive a BEV, a suitable motor is to be selected and the selection varies based on the vehicle parameters and the dynamics. Most of the BEV are using brushless DC motors (BLDC) or permanent magnet synchronous motors (PMSM) with outer rotors integrated into wheels. These motors utilize a battery and ultra-capacitor (UC) as hybrid energy storage system (HESS) to provide electric propulsion [17]-[22]. The direct drive layout employed in this vehicle is highly efficient and offers excellent potential for a long lifespan, making it a promising option for EV [23]. The gearless design of this vehicle provides improved dependability and reduces noise output. Moreover, the design with fewer mechanical parts lowers the frequency and severity of necessary repairs [24]-[27].

2. PROPOSED METHOD: HYBRID ENERGY STORAGE ELECTRIC VEHICLE MODELLING

Figure 1 depicts the configuration of the powertrain in the vehicle, where the energy storage systems, namely the battery pack and UC, are interconnected to the common DC bus through two DC/DC interleaved converters. This arrangement enables the hybrid source to be fully operational, facilitating efficient power distribution between the two storage systems and allowing the output voltage of the source to be adjusted using bidirectional converters in a parallel active topology. The BLDC motor, which is situated in the powertrain, is energized by DC/DC converters, and is connected to the gearbox and ultimately to the Final drive of the vehicle. The vehicle control unit is responsible for vehicle control, while the energy management (EM) system governs the control of the energy sources. In this research paper, an analysis of the power management in a HESS is carried out.

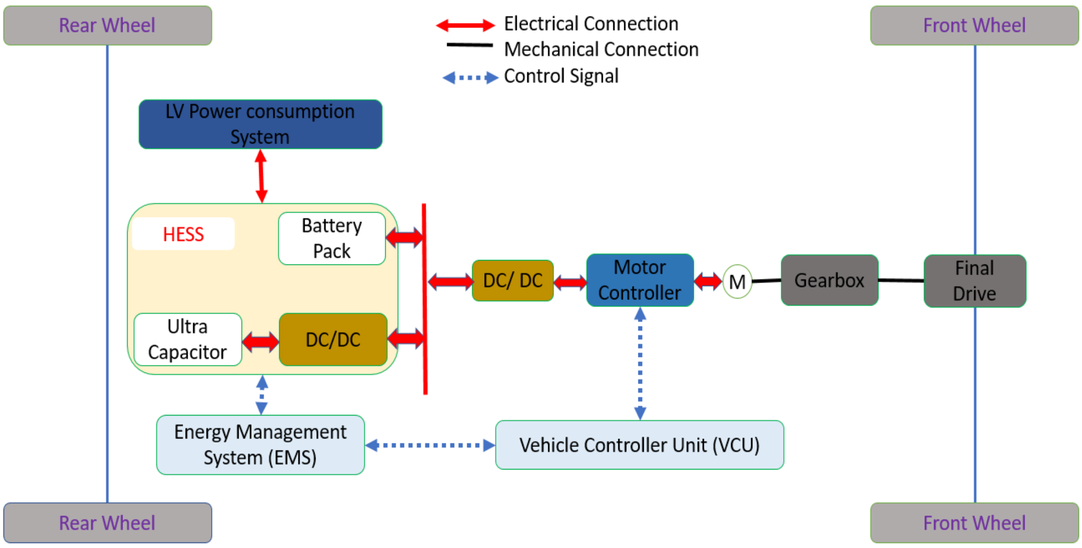

Figure 1. Intricate composition of HESS in EV

2.1. Vehicle modelling

To simulate the EV, simulation involved with EM is crucial. The study involved the model of the vehicle’s longitudinal dynamics, engine model, and HESS model. The motor models. Motor models are created with an environmental approach to ensure accuracy and reliability [22], while the other models are constructed through mathematical modelling. DC bus is linked with battery module and UC module. DC bus is directly connected whereas the UC module uses a bidirectional DC/DC converter to communicate with the DC bus. Maximum energy can be delivered to the vehicle with little power drain on the system due to the DC/DC converter's ability to regulate the UC's output power. To model a hybrid electric car, it is necessary to analyze a simulation experiment incorporating EM. The HESS utilizes a buck-boost bidirectional DC/DC converter to regulate power, and a model of this converter is developed based on its design principles and parameters. The overall structure of HESS is illustrated in Figure 2.

The ongoing investigation entails the creation of a prototype automobile that incorporates a driver model, a model of the vehicle's longitudinal dynamics, an engine model, and a HESS. While the motor model is formulated through empirical testing, the remaining models are formulated through mathematical modeling techniques. Within this research, the battery module is directly connected to the DC bus, whereas the UC module is linked to the DC bus via a bidirectional DC/DC converter. This configuration exemplifies a UC semi-active hybrid topology, which enables efficient power management between the two energy storage systems. The DC/DC converter is also capable of regulating the UC's output power to optimize vehicle power output while minimizing the overall power train system and extending battery lifespan [11]-[15].

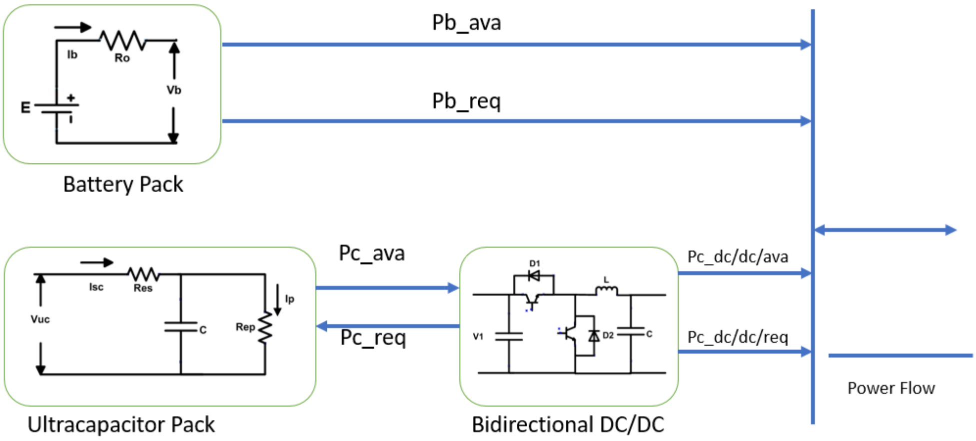

Figure 2. HESS model

To refine the HESS model, parameters related to the ultra capacitor (UC), battery and DC/DC converter are adjusted, the battery model employs the internal resistance (R_{int}) equivalent circuit, is considered the most suitable option. Experimental tests can be conducted on the power battery model to determine its open circuit voltage and internal resistance as a function of state of charge (SOC) and temperature. Parameters and rating of maxwell BCAP0650 automotive are utilized for simulating UC [16].

2.2. Design of ultra capacitor

Equivalent circuit is shown in Figure 3, consists of equivalent series resistance (ESR) and series combination of equivalent parallel set of capacitance and equivalent parallel resistance (EPR). To indicate the charging, discharging of UC, self-discharging, and losses are shown with ESR and EPR respectively. Only the ESR will be considered, as the EPR does not model the influences of long-term energy storage (ES) performance and leakage effects of UC. As a result, the voltage profile will be determined by the interaction of two variables: capacitance and resistance. In this analysis, MATLAB and Sim Power Systems were used to develop the UC bank model.

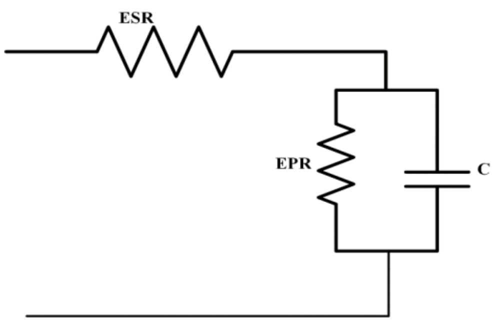

Figure 3. UC unit equivalent circuit

2.3. Power conditioning unit

Interface of power conditioning unit (PCU) is required when more than one power source is used. To control and make the sources work with control over current, PCI is needed. In addition to allowing the wheel's power to be distributed between the battery system and the UC bank, this interface also allows the fuzzy logic controller (FLC) to enforce its rules for how that power is distributed. Two separate DC-DC converters make up the PCU's framework; one connects to the battery system, while the other communicates with the UC bank. A current-fed to the full bridge DC-DC converter is used to guarantee the correct amount of power is transmitted from the battery system to the motor train. To allow for future upgrades, a high frequency transformer is employed to isolate the battery system from the drive train and boost its input voltage. In addition, it is proven that a battery system's output current fluctuation can be effectively reduced with the use of an input inductor [21]. In addition, the converter's switching sequence (duty ratio larger than 0.5) ensures that the required current from the battery system is continuously supplied, extending the battery system's useful life.

3. METHOD: SCHEME OF POWER MANAGEMENT

To ensure proper energy flow to and from the UC, which cannot store energy required for accelerating to maximum speed, the power management in HESS needs to be regulated [17]. To provide an example, if UCs begin assisting too early, they might deplete their energy reserves prematurely, rendering them unable to assist when higher speeds are required. Conversely, when we only consider the most intense power surges, UCs are often not utilized to their full potential. For instance, keeping the UCs at a high SOC during moderate-speed driving can impede energy recovery during braking, highlighting this concern. To effectively control the power distribution in this hybrid system, a FLC has been developed. This controller offers greater design flexibility compared to conventional control methods, making it well-suited for this type of HESS. The FLC uses Sugeno rules which predict the behavior of complex systems.

The control approach shown in Figure 3 is a closed loop system that uses FLC to determine the optimal reference current for each of the two DC/DC converters. The reference current values are then fed into the current control loops of the converters to regulate the power flow between the battery and UC. The FLC input from various sensors including vehicle speed, SOC of the battery and UC and the power demand from the motor, based on these inputs, the FLC calculates the optimal reference current values for each of the converters. The closed loop control system continuously monitors the output voltage of the hybrid source and the UCs to ensure they remain constant and optimal. By using this control approach, the power management system can efficiently distribute power between the two energy sources and maintain the desired system performance.

The power demand of the vehicle is affected by the terrain. When driving uphill, the power required is high and acceleration is high. Resulting the lower energy recovery, thus necessitating a larger energy reserve. However, when driving downhill, less energy is consumed, and more energy is recuperated during deceleration [19]. The sharing of data can be made possible by utilizing vehicle to vehicle (V2V) communication technology [20].

3.1. Fuzzy logic controls structure

FLCs take in seven inputs and generate UC power and battery power as output variables. This is a popular way to use power ratios as an output from the controller to evenly distribute power between different sources [21], [22]. The absolute power values shown in Figure 4 are the outputs of the power management system. This method makes it easy to transfer power between batteries and can even manage the state of charge of UCs when there's no load power. To manage power flow, a Sugeno-type FLC was used (zero order). The input variables for the FLC include output voltage error of the hybrid source Uerr, Pload (power load), velocity v, voltage from UCs Ucap, square of seed normalized to max, square of UCs voltage ($Ucap^2$), and terrain slope (δslope). The slope factor is determined by (1):

$$\delta_{slope} = \frac{1}{3}\,[h(100) - h(0)] + \frac{1}{6}\,[h(200) - h(0)] + \frac{1}{9}\,[h(300) - h(0)] \tag{1}$$

$$= \frac{6.h(100) + 3.h(200) + 2.h(300) - 11.h(0)}{18}$$

Battery life (p_{bat}) and UCs power (p_{uc}) are the outcome variables (pcap). The membership functions at the output are always zero (0), char (S)=20, char (L)=50, and disch (L)=20. Figure 5 shows fuzzy interface system which takes the input rules of battery voltage error, load, voltage of capacitor, speed inputs given to FLC HESS block. FLC HESS operates with 61 rules and the output is input parameters to battery and UC in terms of power. Figure 6 is detailed with the member ship functions of UCs inputs with Sugeno rules. The degree of membership in Figure 6(a) is battery voltage at NL, NS, ZE, PS, and PL. Figure 6(b) is detailed with the load inputs at membership functions of low, high, very high, and medium states. Figure 6(c) describes the membership functions (MF) of low, medium, and high voltages, also the over voltage and under voltages. Figure 6(d) inputs the speeds of low high and zero inputs.

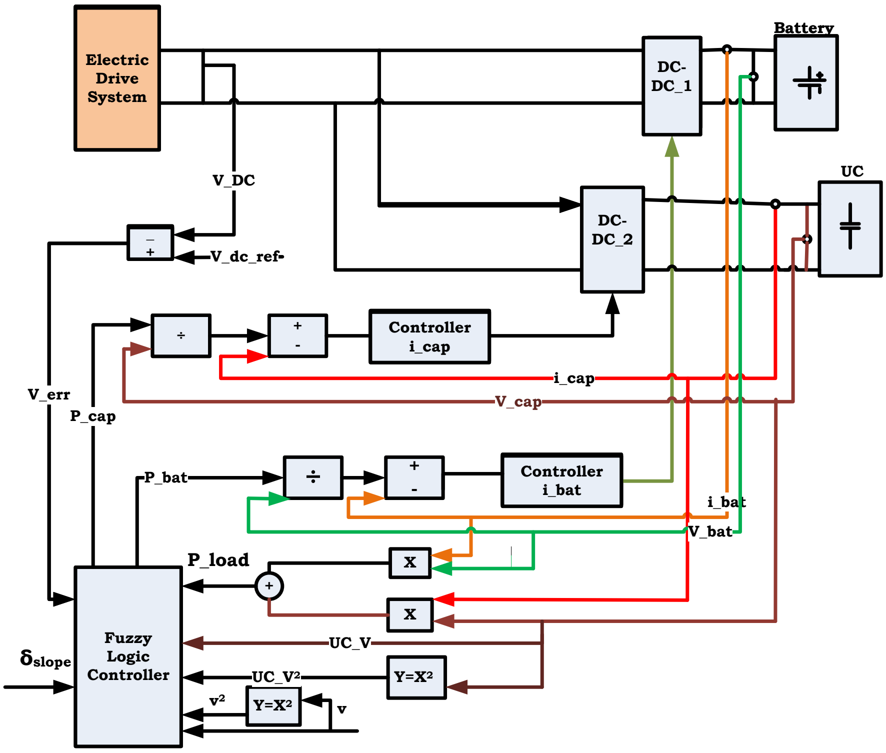

Figure 4. HESS control scheme

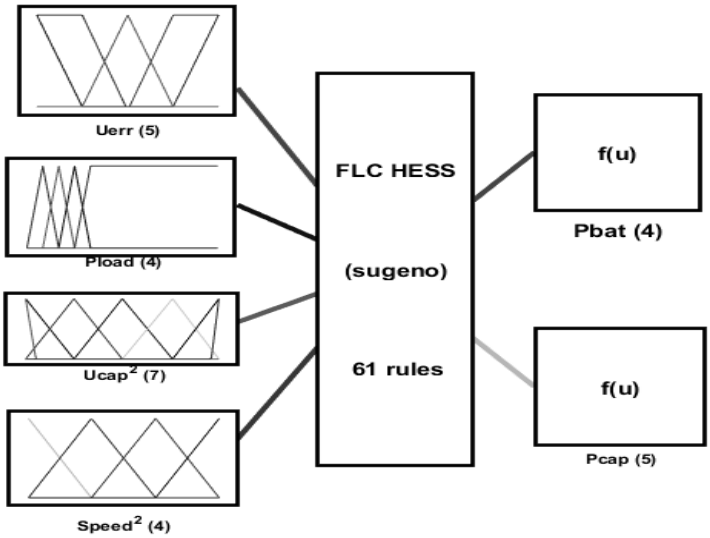

Figure 5. Fuzzy inference system

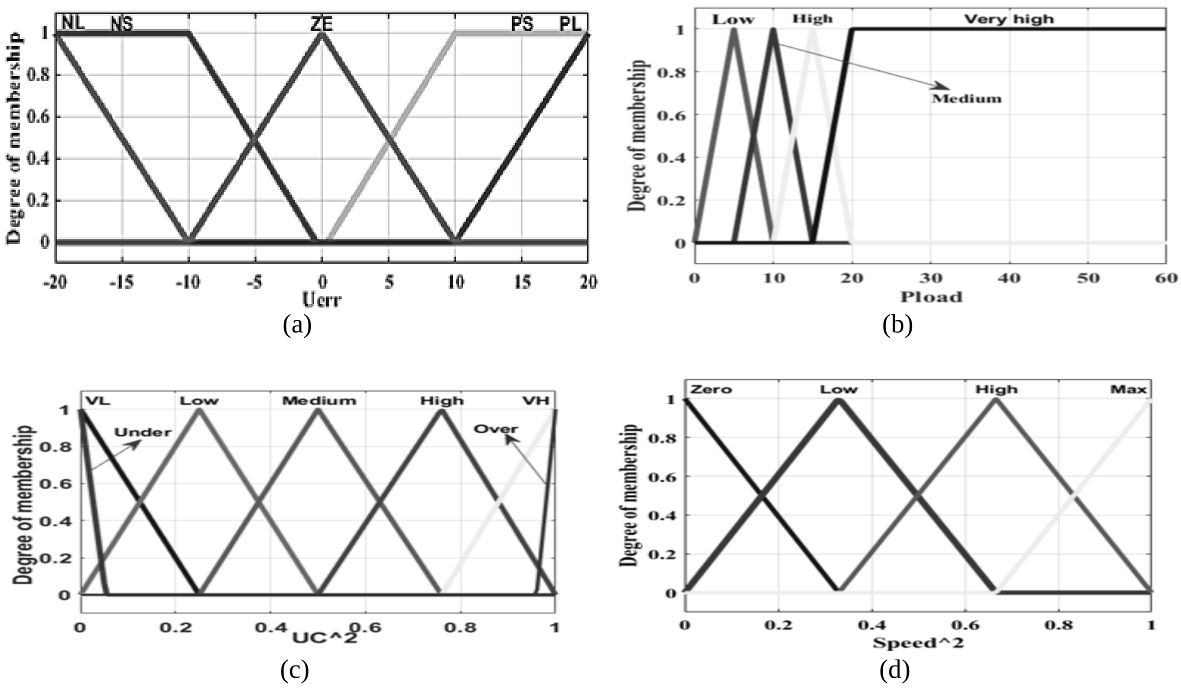

Figure 6. MF for input and output; (a) MF for error, (b) MF for load power, (c) MF for ultra-capacitor input, and (d) MF for speed

4. RESULTS AND DISCUSSION

SOC variation while charging and discharging the battery is shown in Figure 7. Further, Figure 8 illustrates all the voltages, encompassing those from the load, UC, the battery, and the DC link voltage and its comparison. This denotes that the battery and UC modules have reached their full charge. The battery voltage corresponds to the battery voltage reference, while the UC voltage corresponds to the UC voltage reference. Upon reaching t=4 s, the motor commences its operation, attaining its peak speed of 800 rpm, thereby supplying battery and UC power to the load in a stable state. As a matter of fact, the following:

- Most of the momentary energy needed for motor acceleration is provided by the UC module.
- The dynamics of UC power are the quickest, those of battery power are intermediate, and those of EV power are the slowest.

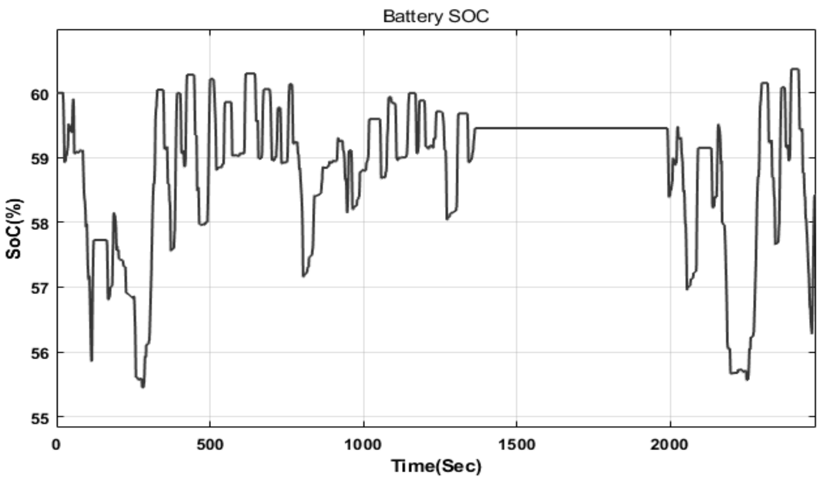

Figure 7. Simulation result for battery SOC during charging and discharging

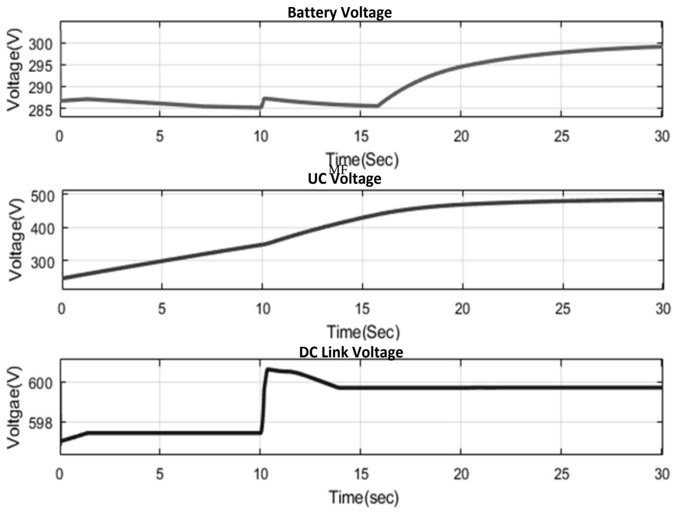

Figure 8. Results of battery, UC, and DC link voltage

- Simultaneously, the UC power tapers down progressively to a consistent discharge level of approximately 160 W, following an initial sharp surge (discharge) during motor acceleration. Both the battery and UC system jointly deliver the full steady-state load power of approximately 600 W. EV draws a peak current of 25 A, with a constant 20 A draw from the battery module sustained throughout the discharge phase.
- Figures 9 and 10 depict the power variation of battery power, UC power and load power respectively. Figure 10 shows how the power balance management occurred the system under hybrid energy storage component. Ultimately, DC link voltage comparison diagram of different strategies waveforms are shown in Figure 11; they were acquired very good dynamic performance of system and the DC link provide voltage during motor is in regenerative braking.

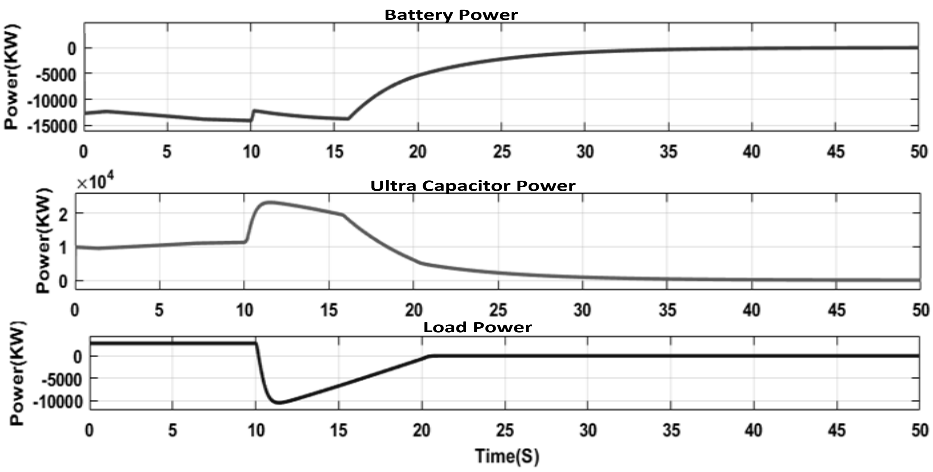

Figure 9. Battery power, UC power, and load power comparison at different operating zones

- Initially, the UC recharges the EV's battery, the DC link, and the motor via regenerative braking.
- The second function of the power source is to charge the ES devices such as the UC and the batteries.
- When the UC module is almost completely charged, electrical power is gradually reduced until it is just charging the battery module.
- The UC module is fully charged, as indicated by the equation $V_{SuperCREF}=V_{SuperC}$. As a result, the power is just sufficient for battery charging.

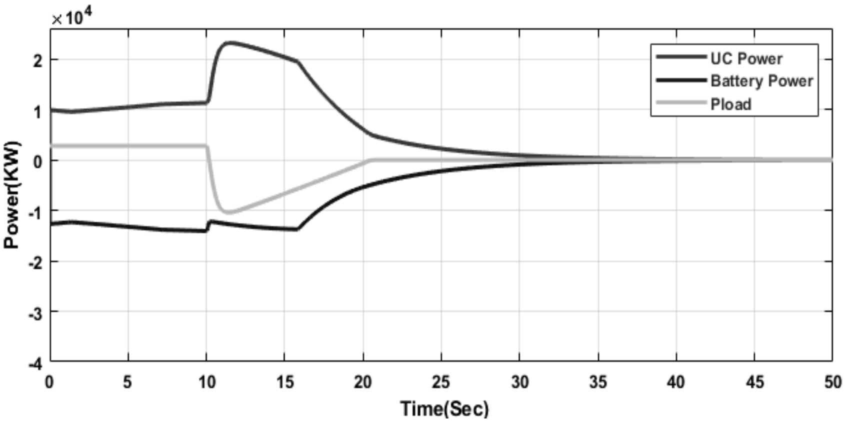

Figure 10. Combined view of UC power, battery power, and load power

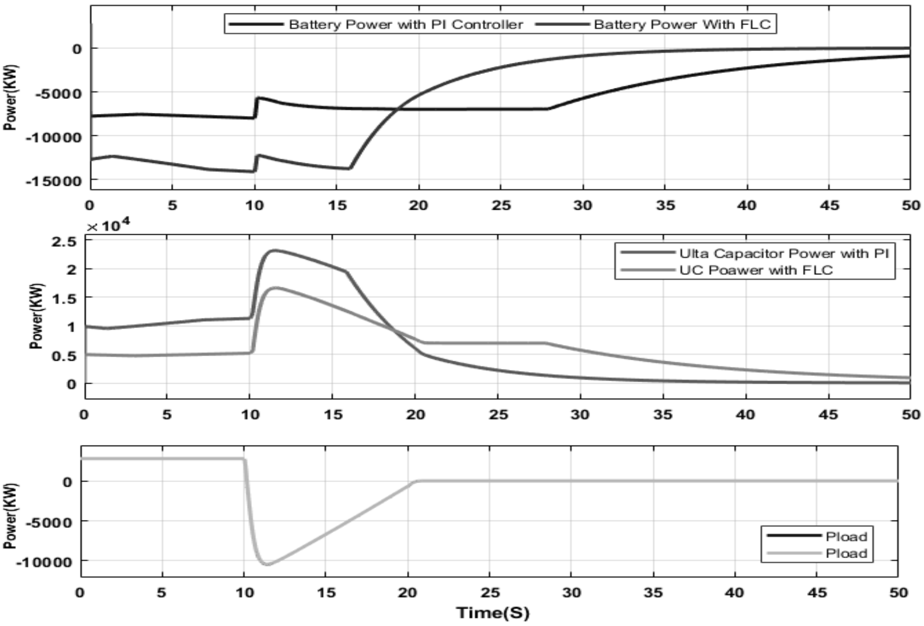

Figure 11. Power variation of battery, UC, and load

While using the proposed EM hybrid power source, the dynamics of the EV and battery powers are decreased, and the DC bus voltage hardly varies at all during motor start/stop.

The controller is used to perform the above said hybrid storage EM. PI controller and FLC are used to operate the battery in closed loop operation. Figure 11 shows the comparison of battery power, UC power and load power when controller used is PI controller and FL controller. The tabulation shown in Table 1 gives the comparison of battery parameters with the two controllers PI and FLC.

Comparison of voltage value with time is shown in the Figure 12. Portion of variation is zoomed to show the voltage variation with PI controller and FLC controller to understand the DC voltage comparison. The different parameters of the battery are tabulated in Table 1. This shows that the battery decay rate is reduced with EM used with FLC controller compared with PI controller and distance covered by the EV increased with FLC over PI controller device.

Table 1. EM comparison with different strategies

Parameters	EM based on PI controller	EM based on fuzzy controller
Battery maximum current measured (A)	212.65	183.15
Battery degradation rate (%)	11.87	10.234
Travel range with battery in km	118.43	143.15
Energy consumption battery	14.13	11.72

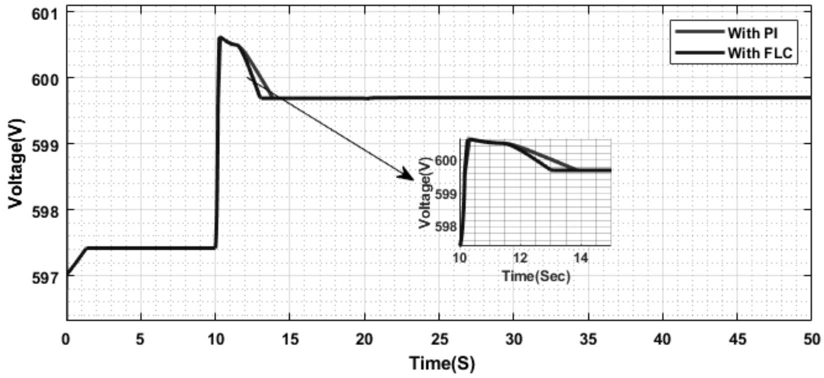

Figure 12. DC voltage comparison with FLC and PI controllers

5. CONCLUSION

For EVs, a battery-UC energy storage system is developed and modelled. It has been demonstrated in MATLAB those electrochemical batteries may be reliably supported by even a small amount of extra UC energy storage. The HESS's FLC approach has been developed and tested in simulation. This suggests that incorporating additional data, such as traffic volume, could potentially boost the efficiency of the hybrid source. Soon, information of this kind will be streaming in from the road itself and the vehicles ahead of us. The power management system will have access to such information at no extra expense. There are plans to improve the FLC in a later version of this paper by adding new input signals and more rules that consider things like the average speed throughout the route.

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