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PERFORMANCE OF ELECTRICAL VEHICLE USING FUZZY LOGIC CONTROLLER BASED ON HYBRID ENERGY STORAGE

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ABSTRACT

For the hybrid energy storage system, the paper proposes an optimal control algorithm designed using a Li-ion battery power dynamic limitation rule-based control based on the SOC of the super-capacitor. Using a dc-link voltage-regulated PI-based controller, magnetic integration technology with a second-order Bessel low-pass filter is simultaneously introduced to DC-DC converters of electric vehicles. The PI controller gives more harmonic distortion and less accurate results. In place of the PI controller, a fuzzy logic controller was used to reduce harmonic distortion and error value. The proposed method evaluates the results in terms of voltage, current, and power. The proposed method's and conventional method's results were compared using MATLAB and Simulink software.

Keywords: Hybrid Energy Storage System, Integrated Magnetic Structure, Electric Vehicles, DC-DC Converter, Power Dynamic Limitation, Fuzzy Logic Controller.

I. INTRODUCTION

Due to the pollution caused by fossil fuel, new energy sources have been continuously developed. Nowadays, embedded energy storage systems in current generation electric vehicles are mostly based on the Li-ion batteries which, with high energy density, can provide long distance endurance for electric vehicles. While compared to the super capacitor, the response of Li-ion batteries is slower than that of super capacitors. Therefore, in order to make electric vehicles comparable to fuel vehicles with regards to fast transient acceleration, energy, and long-distance endurance, a hybrid energy storage system (HESS) consisting of Li-ion batteries and super-capacitors is applied to electric vehicles. For the development of electric vehicles, optimizing the energy storage device is critical, and it is necessary to consider increasing the capacity of the battery, while reducing the size and weight of the battery to increase the charging rate. DC-DC converters which play an important role in hybrid energy storage system have been developed rapidly over the years.

Through a series of innovations, a variety of DC-DC converters are proposed. A new zero Voltage Switch (ZVS) bidirectional DC-DC converter is proposed in, which has good controllability to improve conversion efficiency, but is not suitable for electric vehicles due to the complex control and higher cost. It has been shown an isolated bi-directional DC-DC converter with complex structure is able to convert a large power transmission. A new zero-ripple switching DC-to-DC converter with the integrated magnetic technologies is first proposed in by S.Cuk, and the application is very successful. Isolated interleaved DC/DC converter introduces the concept of three-winding coupled inductors, but it is more suitable for power transmission. It is very important for hybrid energy storage systems to select a suitable energy management strategy. Energy management strategies have been extensively reported in literature in the recent years, including neural networks, fuzzy logic, state machine control, frequency decoupling method, on/off-line optimal strategies, dynamic programming (DP) and limitation of battery power. The main objective of the optimal control strategies is to ensure a continuous.

II. TOPOLOGY OF HYBRID ENERGY STORAGE SYSTEM

Fig. 1 is a proposed hybrid energy storage system Composed of DC/DC converter, super capacitors and the Li-ion battery. DC/DC converters consist of four IGBT switches T1~T4 and its corresponding diode (added battery) tube D1~D4, and an integrated magnetic structure self-inductance L1, L2 and mutual inductance M, which share a core inductor. The battery pack provides power to the smooth DC motor. The super capacitor deals with the instantaneous state of peak power supply. The power management system of electric vehicles determines the electrical energy flow according to the load demand.

The converter has five main operating modes (mode due to the additional battery pack change). Table 1 shows the specific operation mode of hybrid energy storage system corresponding energy flows and operating mode DC-DC converter.

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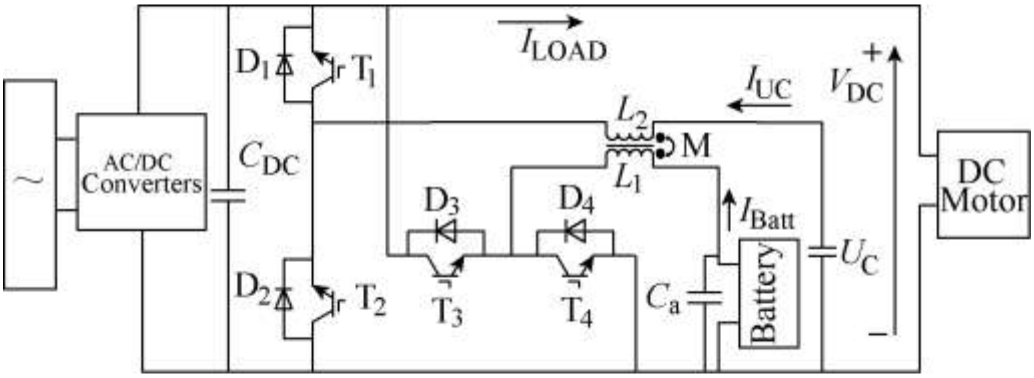

Fig 1: Topology of the hybrid energy storage system

Design of the DC/DC converter with integrated magnetic structure

Magnetic elements such as inductors, are the main components of energy conversion, filtering, electrical isolation and energy storage. The size of the magnetic element is a major factor in determining the size and weight of the converter. To achieve the integration of magnetic elements, an E-type magnetic core is used in this paper. Herein, accoupling inductance (L1 and L2) is used. As shown in Fig.2, L2 as the output filter inductor, L1 as the external inductance, and Ca as additional capacitance. In the steady state, the voltage of Ca is equal to the output voltage of L2 and L1 without regard to the capacitor voltage ripple. The DC/DC converter of Fig.1 consists of4 IGBT switches (T1~T4) and 4 diodes (D1~D4). As a boost converter, there are two operational modes (consisting of L1, T4, D4 or L2, T2, D1); and as a buck converter, there also are three operational modes (consisting of L1, T3, D4 or L2, T1, D2). It can be seen from Table 1, a comparison of two structures of DC/DC converter is illustrates that the volume and weight of the DC/DC converter with integrated magnetic structure are reduced. In the electric vehicle, the application of the DC/DC converter with integrated magnetic structure can reduce the overall size and weight of the energy storage system. Moreover, integrated magnetic structure can reduce the output current ripple. In section 4, the effectiveness of the integrated magnetic structure is validated by simulation.

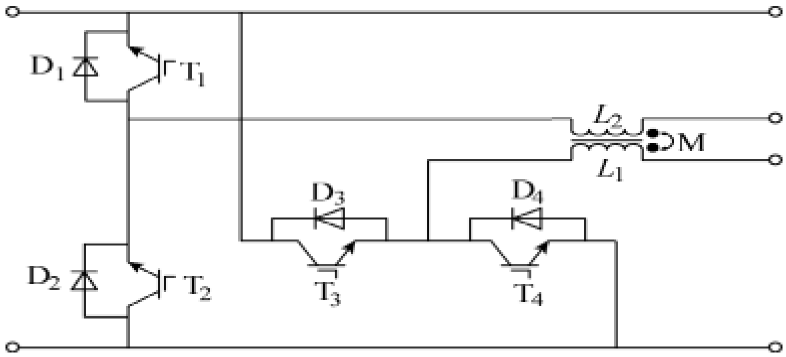

Fig 2: Topology of DC/DC converter with integrated magnetic structure

Table 1: Operation mode of Hybrid Energy Storage System

Working mode	Power source	Power flow	Operation mode
Parking charging mode	AC Power	Battery and super capacitor	Buck
Constant speed mode	Battery	DC	Boost
Acceleration mode	Super capacitor	DC Motor	Boost
Breaking mode	Breaking energy	Battery and super capacitor	Buck
Super-capacitor charging mode	Battery	Super capacitor and DC motor	Boost or Buck

Control strategy of hybrid energy storage system

Super capacitor

A cascade voltage and current controller is selected to provide a stable load voltage. When the DC side voltage has a significant increase during braking, Super-capacitors can make a more rapid response and recycle the braking energy. Fig.3 is the control block diagram of the super capacitor controller. Where Vdc and Vdc-sen are respectively the actual voltage and rated voltage of DC motor; * iUC and * iUC􀀀sen are respectively the per unit of super-capacitor actual current and rated current; fs is the switching frequency; G1,2 is the switching signal of T1 and T2. In boost mode, the duty cycle of the inductor current transfer function can be expressed as

$$\frac{I_{L2(s)}}{D_{(s)}} = \frac{V_{dc} R_{Load} C_{dc} s + 2V_{dc}}{R_{Load} L_2 C_{dc} s^2 + L_2 s + R_{Load}(1-D)^2} \quad (1)$$

IL2(s) is the reference current of L2, Vdc is the DC motor voltage, Cdc is the capacitor DC motor, D is the duty cycle. In the frequency range, the relationship between the inductor current and the DC-side voltage is represented by the following equation

$$\frac{V_{dc}(s)}{I_{L2}(s)} = \frac{-L_2 s + R_{Load}(1-D)^2}{R_{Load} C_{dc}(1-D)s + 2(1-D)} \quad (2)$$

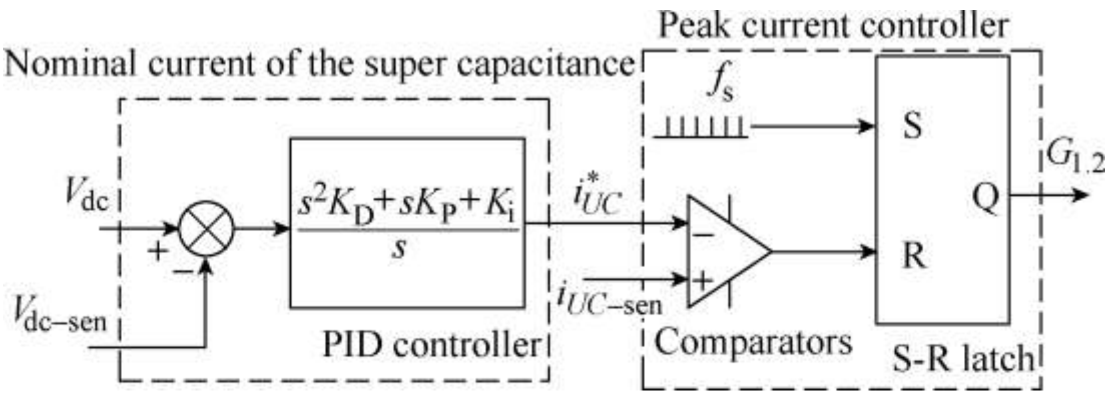

Fig 3: Block diagram of the super-capacitor voltage and current controller

Li-ion battery

The battery pack control can produce a smooth supply of the DC motor current. The second-order cut-off frequency of 50Hz Bessel low-pass filter has been applied to reduce output current ripples or avoid instantaneous s large changes. Assuming the converter is lossless, the DC motor current is equal to the battery current, which can be expressed as:

$$V_{load} \times I_{load} = V_{batt} \times I_{batt}; I_{batt} = \frac{V_{load} \times I_{load}}{V_{batt}} \quad (3)$$

The reference current of the battery pack is expressed as:

$$I^*_{batt} = \frac{V_{load} \times I_{load}}{V_{batt}} G_{LP}(s) \quad (4)$$

Where Vload and Iload stand for the voltage and current of DC motor; Vbat and Ibat are the voltage and current of Li-ion battery. GLP (s) is the transfer function of Bessel low-pass filter which can be expressed as: are the reverse Bessel polynomials, 􀀀 0 is the cutoff frequency, a(n) and b(n) are coefficient of the Bessel polynomials. The Bessel filter is a linear filter with the largest flat group delay or linear phase response and can fully retain a

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filtered waveform and maintain a stable group delay. Once the battery output reference current is established, the converter is controlled by the peak current controller. Fig.3.3 is a specific control block (where * ibatt and * ibatt-sen are the per unit of actual and rated battery current; G3,4 is the switching signal of T3 and T4). Moreover, Li-ion battery power dynamic limitation rule-based control based on the SOC of the super capacitor is introduced to avoid the frequent switch of Li-ion batteries (charge and discharge) and reduce the stress on the Li-ion batteries. The operating modes are as follows:

$$G_{LP}(s) = \frac{\theta_n(0)}{\theta_n(s/\omega_0)} = \frac{b(1)s^n + b(2)s^{n-1} + \cdots + b(n+1)}{s^n + a(2)s^{n-1} + \cdots + a(n+1)} \quad (5)$$

Mode1: When the HESS is charging, if the SOC of super-capacitor exceeds the upper limitation Qsc_char_high, the limitation of Li-ion power is increased to Pchar_high_limit;

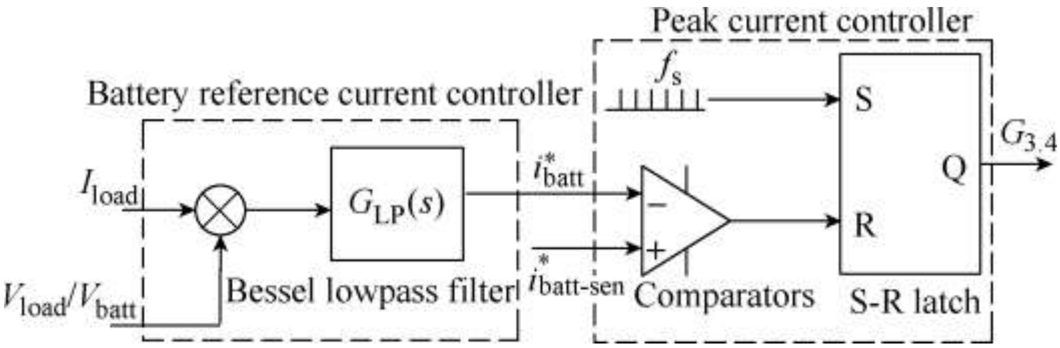

Fig 4: Block diagram of the Li-ion battery pack

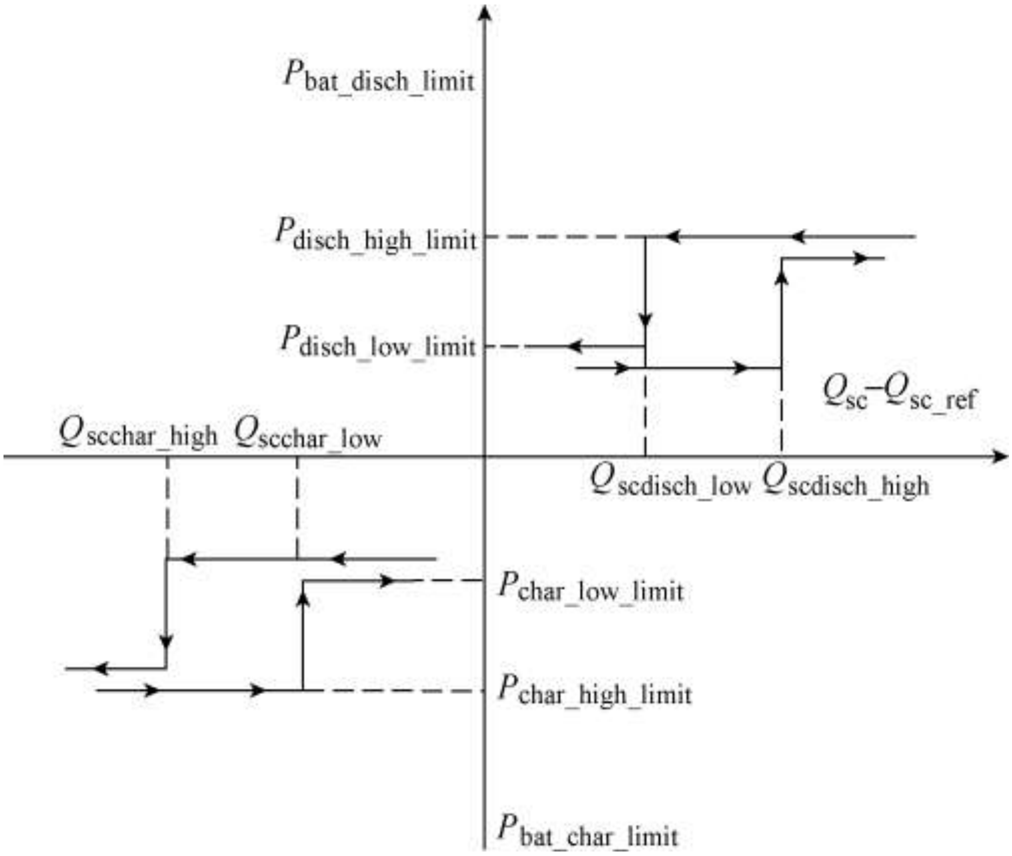

Fig 5: The diagram of Li-ion battery power dynamic limitation

if the SOC of super-capacitor is lower than the lower limitation Qsc_char_low, the limitation of Li-ion power is reduced to Pchar_low_limit. The dynamic limitation of the Li-ion battery can be written as:

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$$\text{If } Q_{sc} - Q_{scref} \geq Q_{scchar\_high},$$
$$P_{bat\_char\_limit} = P_{char\_high\_limit} \quad (6)$$
$$\text{If } Q_{sc} - Q_{scref} < Q_{scchar\_low},$$
$$P_{bat\_char\_limit} = P_{char\_high\_limit} \quad (7)$$

Mode 2: When the HESS is discharging, if the SOC of super-capacitor exceeds the upper limitation Qsc_disch_high, the limitation of Li-ion power is increased to Pdisch_high_limit; if the SOC of super-capacitor is lower than the lower limitation Qsc_disch _low, the limitation of

Li-ion power is reduced to Pdisch_low_limit. The dynamic limitation of the Li-ion battery can be written as: The above control parameters can be acquired by a hybrid algorithm based on particle swarm optimization and Nelder-Mead simplex approach.

Continuous recharge of super-capacitor from Li-ion battery

In order to ensure enough energy from the supercapacitor, when the SOC of the super-capacitor is below the limit, the super-capacitor charges from the Li-ion battery. Moreover, in the beginning of the driving cycle, a target value of super-capacitor SOC is chosen as the initial value to provide enough energy. An additional control loop based on PI controller, which controls the continuous recharge of super-capacitor from Li-ion battery during the driving phase and also when the electric vehicle is at a standstill, is designed. Fig.6 is a specific block of the additional control loop.

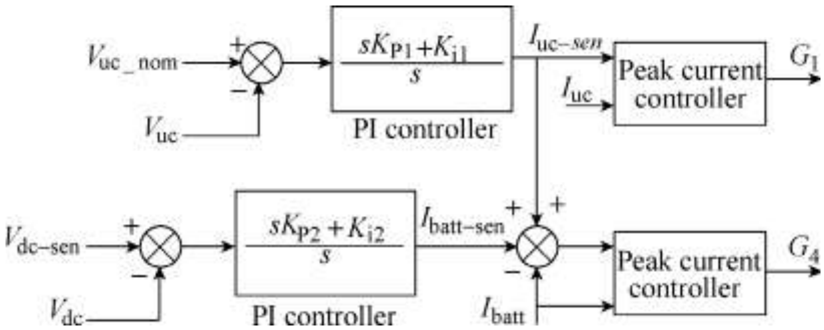

Fig 6: Block diagram of additional control loop

Where Vuc_nom and Vuc are the rated and actual super-capacitor voltage; Iuc-sen and Iuc are the rated and actual super-capacitor current; Vdc-sen and Vdc are the rated and actual voltage of DC motor; Ibatt-sen and Ibatt are the rated and actual battery current; G1,4 are the switching signal of T1 and T4.

Control parameter optimization

The optimization of HESS energy is targeted to solve a mathematical multi-constrained nonlinear problem. It can be described in the following equations:

$$\min xF(X) = \{f(X)\} \quad (10)$$

to:

$$g_i(X) \leqslant 0, i = 1,2,3,4 \quad (11)$$

$$X_{min} \leqslant X \leqslant X_{max} \quad (12)$$

Where is X =(x1, x2,..., x10) is the control parameter; x1, x2, x3, x4, x5, x6, x7 and x8 represent Pdisch_high_limit, Pdisch_low_limit, Qsc_disch_high, Qsc_disch_low, Pchar_high_limit, Pchar_low_limit, Qsc_char_high and Qsc_char_low; x9 and x10 are PI control parameters to ensure that the energy of super capacitor is kept around its beginning value at the end of each driving cycle (KP1 and Ti1). In order to reduce the stress of the Li-ion battery pack, the HESS energy management proposed in the paper is designed to reduce the instantaneous power of the Li-ion battery pack under the premise of ensuring the performance of HESS. Therefore, a function aiming at minimizing the battery power RMS of the Li-ion battery is established as shown in Equ.(13).

$$f(X) = \sqrt{\frac{1}{T}\int_0^T P_{\text{Bat}}^2(t)\mathrm{d}t} \qquad (13)$$

Where T is a time period covering full charging and discharging cycles; PBat(t) is the instantaneous power of battery charging or discharging. The hybrid optimization based on particle swarm optimization and Nelder-Mead simplex approach of control parameters is as follows: (1) Initialize particles and calculate fitness values for each particle. Then find local position (LP) and assign LP to global position (GP). F(LP)=min{fi} (2) Particle swarm optimization: Calculate velocity for each particle and update each particle's position; Then evaluate each particle fi =F(Xi) and find LP, if the LP better than GP, assign LP as new GP; Otherwise, keep it. When iteration＞m1, go to the next step. (3) Nelder-mead simplex approach: Define verticles GP, LP, WP (worst position F(WP) = max {fi}); Then, reflect, expanse, contract, shrink the vertices; Evaluate each particle fi =F (Xi); and find LP, if the LP better than GP, assign LP as new GP; Otherwise, keep it. When iteration＞m2, end. Li-ion battery power constraints:

$$E_{\text{Batcons}} \leqslant N_{\text{SB}} \cdot N_{\text{PB}} \cdot C_{\text{celbat}} \cdot U_{\text{celbat}} \cdot \eta_{\text{DOD}} \qquad (14)$$

$$P_{\text{Batcons}} \leqslant N_{\text{SB}} \cdot N_{\text{PB}} \cdot C_{\text{celbat}} \cdot I_{\text{cel\_bat}}^{D} \qquad (15)$$

$$P_{\text{Batrec}} \leqslant N_{\text{SB}} \cdot N_{\text{PB}} \cdot C_{\text{celbat}} \cdot I_{\text{cel\_bat}}^{C} \qquad (16)$$

Where EBatcons is HESS energy consumption; NSB.NPB is the Li-ion battery cells; NSB is the number of cells in series and NPB is the number of cells in parallel; Ccelbat、 Ucelbat are respectively the rated capacity and cut-off voltage of Li-ion battery cells; DOD is the discharge

depth; cel_bat I D and cel_bat I C are respectively the discharging current and charging current of Li-ion battery; PBatcons and PBatrec are respectively the peak lithium battery discharging and charging power; Super-capacitor power constraints:

$$\Delta E_{\text{sc}} \leqslant \frac{3N_{P\_\text{sc}}}{8N_{S\_\text{sc}}} \cdot C_{\text{celsc}} \cdot U_{\text{sc\_max}}^2 \qquad (17)$$

Where Esc is the energy requirement of supercapacitor to fulfill the transient powers (Esc = Esc_max Esc_min), NP_sc, NS_sc are the number of Super-capacitor branches in parallel and in series; Ccelsc, Usc_max are the rated capacity and maximum peak of the super-capacitor output voltage.

Table 2: HESS Parameters

Parameters	Values
$N_{SB}.N_{PB}$	185
NP_sc. NS_sc	570
Li-ion battery η DOD	80 %
Li-ion battery initial SOC	1
Super-capacitor initial SOC	0.94
Li-ion battery En/(kW·h), P_{max}/W	10, 200
Super-capacitor En/(kW·h), P_{max}/W	0.25,200

Supply by the minimization of a cost function. These strategies can be divided into off-line global optimization and on-line local optimization. For off-line global optimization, it is necessary to acquire the best power distribution between different sources. At the same time, for on-line local optimization, accurate predication driving conditions is necessary. In this work, a new integrated magnetic structure of DC-DC converter is proposed and applied on hybrid energy storage system for electric vehicles. The proposed DC-DC converter gives the specific topology and operating modes, as well as Li-ion battery and super capacitor control. With regards to energy management strategy, the paper proposes an optimization control algorithm designed using a Li-ion battery power dynamic limitation rule-based control based on the state of charge (SOC) of the super-capacitor. In order to improve the life and reduce the size of hybrid energy storage system, the paper uses a hybrid algorithm based on particle swarm optimization and Nelder-Mead simplex approach to optimize the control parameters. Finally, the simulation and experimental analysis verify the hybrid energy storage system performance.

III. RESULTS

Performance of Hybrid Energy Storage Based Electrical Vehicle Using Fuzzy Logic Controller is simulated using MATLAB 2018a. Previously it is PI controller. In this project fuzzy controller is used for better performance. The results based on fuzzy logic controller are given below.

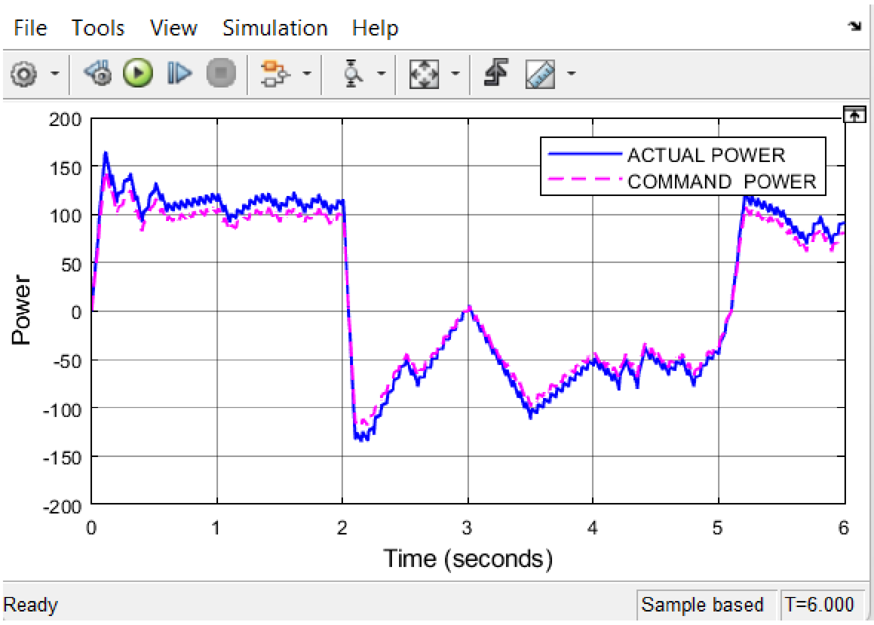

Fig 7: Actual vs Command power in Fuzzy Logic Controller

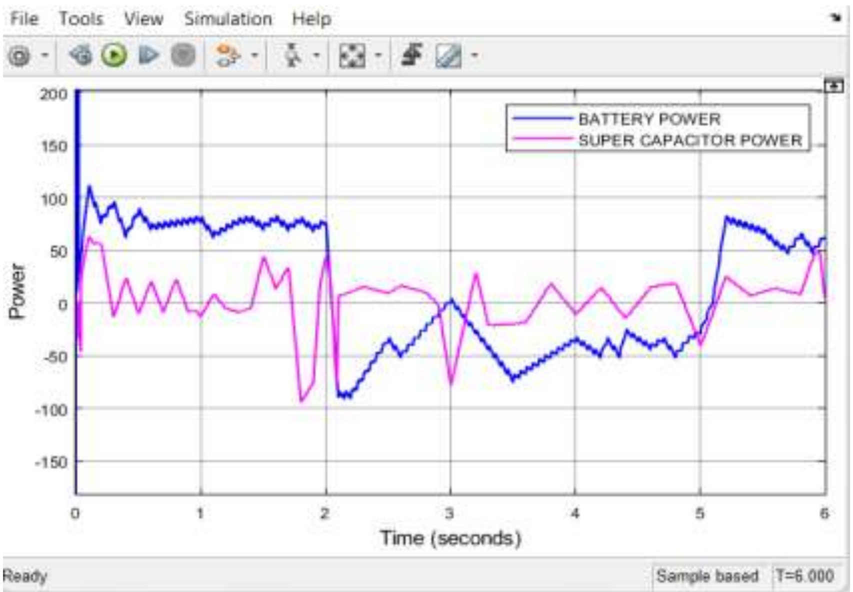

Fig 8: Battery vs Capacitor power in Fuzzy Logic controller

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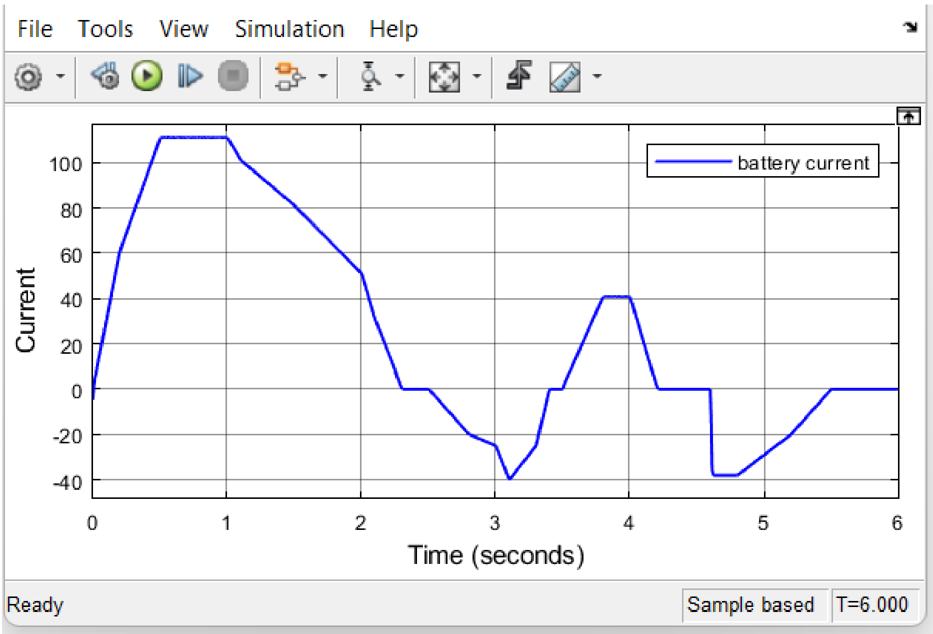

Fig 9: Battery current in Fuzzy controller

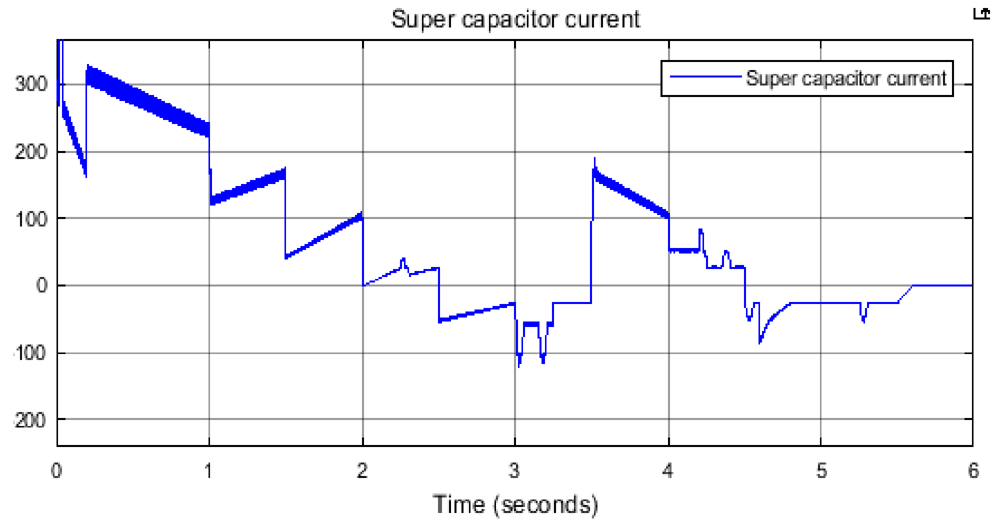

Fig 10: Super capacitor Current in Fuzzy controller

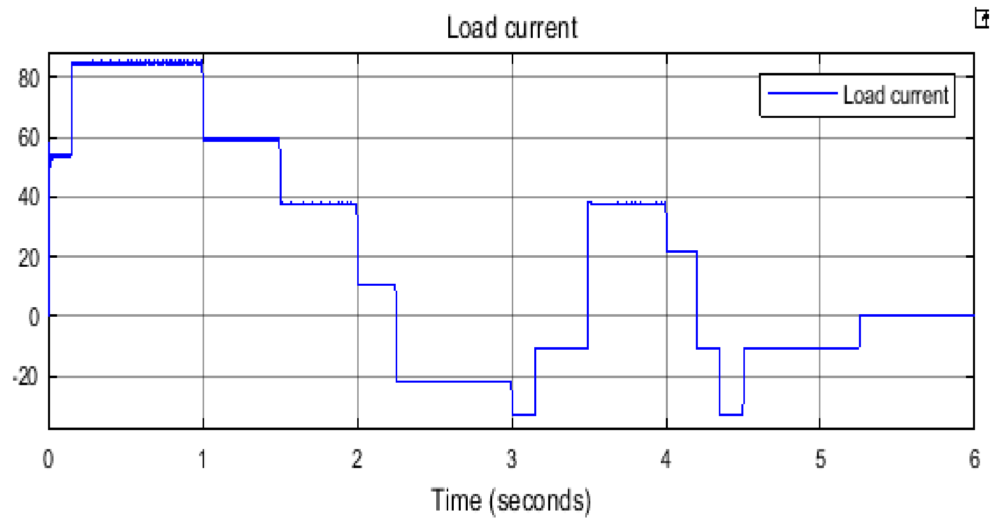

Fig 11: Battery current in Fuzzy controller

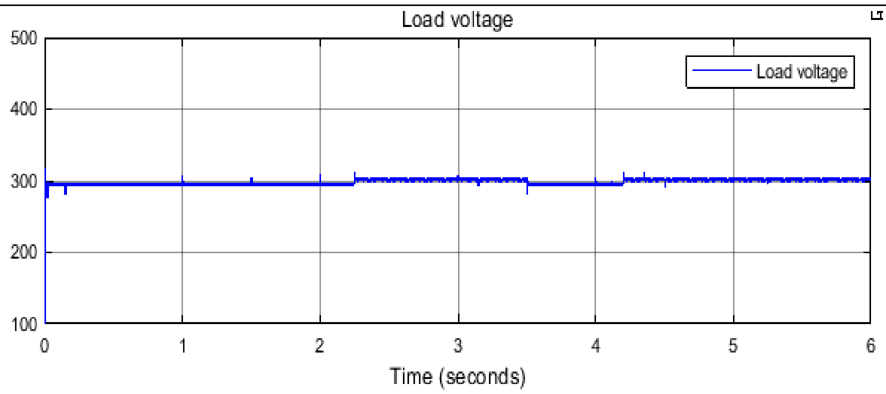

Fig 12: Load voltage in Fuzzy controller

IV. CONCLUSION

This study uses fuzzy logic controller-based evaluation to assess a new hybrid energy storage system for electric vehicles. The research suggests a Li-ion battery power dynamic limiting rule-based control for the hybrid energy storage system that is based on the super-capacitor's state of charge (SOC). Electric vehicle DC-DC converters are simultaneously upgraded with magnetic integration technology and a second-order Bessel low-pass filter using a dc-link voltage-regulated PI-based controller. To lessen harmonic distortion and error value, a fuzzy logic controller was employed in place of the Pi controller. The findings are assessed using the proposed method in terms of voltage, current, and power. Using the software packages MATLAB and Simulink, the results of the suggested method and the standard method were compared.

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