

# Fuzzy Controller Based Efficient Brake Force Prediction with Hybrid Energy Storage System in Regenerative Braking System

Keerthana.P.S<sup>1</sup>, Vandana.P<sup>2</sup>P.G. Student, Department of Electrical and Electronics Engineering, Mar Baselious College of Engineering and Technology, Trivandrum, Kerala, India<sup>1</sup>Assistant Professor, Department of Electrical and Electronics Engineering, Mar Baselious College of Engineering and Technology, Trivandrum, Kerala, India<sup>2</sup>

**ABSTRACT:** Regenerative braking can be used in electric vehicles (EVs) as a process for recycling the brake energy. It is the process of feeding energy from the drive motor back into the battery during the braking process. Complementary features of batteries and supercapacitors can be effectively used in a Hybrid Energy Storage System (HESS). The utilization of the HESS in Electric Vehicles (EVs) offers many advantages such as efficient regenerative braking, battery safety, and improved vehicle acceleration. Fuzzy controller based efficient brake force prediction in regenerative braking system is proposed with BLDC motor. During regenerative braking, the Brushless DC (BLDC) motor acts as a generator. Hence, using appropriate switching algorithm the energy is transferred to the supercapacitor or the battery through the inverter. The harvested energy can be utilized to improve the vehicle acceleration and/or keep the battery pack from deep discharging during driving uphill. To predict the brake force Fuzzy logic controller is utilized. Simultaneously, the speed control of BLDC motor is adjusted by a PI controller and to reduce the ripples in electromagnetic torque of BLDC motor Hysteresis current controller is designed. A new regenerative braking system (RBS) for EVs with HESS and driven by BLDC motor is proposed. In order to evaluate the performance of the proposed system simulations are carried out.

**KEYWORDS:** Brushless DC (BLDC) motor, Hybrid Energy Storage System (HESS), Regenerative Braking System (RBS), Fuzzy logic controller, supercapacitor.

## I. INTRODUCTION

Electric vehicles (EVs) have received much more attention than traditional internal combustion engine (ICE) vehicles. The unprecedented focus is mainly attributable to environmental and economic concerns linked to the consumption of fossil-based oil which is used as fuel in ICE-powered vehicles.. Regenerative braking can be used in EVs as a process for recycling the brake energy, which is impossible in the conventional internal combustion vehicles. Regenerative braking is the process of feeding energy from the drive motor back into the battery during the braking process, when the vehicle's inertia forces the motor into generator mode. In this mode, the battery is considered as a load, thereby providing a braking force to EVs [1]. It is shown that the use of regenerative braking of EVs can increase the driving range up to 45% with respect to EVs without the regenerative braking system (RBS).

Many efforts have been made to use the supercapacitors in EVs to overcome the deficiencies of the batteries. Extreme Hybrid is the first commercialized Plug-in hybrid electric vehicle (PHEV) technology that actively combines batteries and supercapacitors in a HESS, developed by AFS Trinity Power Corporation [2]. There are different configurations for HESS, one of the most studied and researched HESSs is the supercapacitor/battery topology [3] in which the battery pack is directly connected to the DC-bus. A bidirectional DC/DC converter is used to control the power flow between the battery and supercapacitor. Since two individual ESSs and an additional power converter are required for HESSs,

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Vol. 7, Issue 4, April 2018

they are not generally cost efficient. Moreover, the bidirectional converter is necessary to match the power level of the supercapacitor module in order to utilize the capabilities of the supercapacitor, effectively [4]. Therefore, the overall system cost would be high. Here in this paper, a novel structure of desirable interaction of the battery and supercapacitor is proposed. The presented HESS is composed of a supercapacitor module and a battery pack. Two speed cases of the proposed HESS are discussed in details, thus a new RBS is developed.

Paper is organized as follows. Section II describes the mathematical modelling of BLDC motor and section III describes the overall system model. Section IV describes the hysteresis current controller; section V about the Fuzzy logic controller and section VI describe the PI speed controller. The simulation results and conclusion is explained in section VII and VIII respectively.

## II. BLDC MOTOR MODELLING

A 3 phases, 8 poles, Y connected trapezoidal back-EMF type BLDC is modelled. Trapezoidal back-EMF is referring that mutual inductance between stator and rotor has trapezoidal shape. Therefore abc phase variable model is more applicable than d-q axis. With the intention of simplifying equations and overall model the following assumptions are made:

- Magnetic circuit saturation is ignored.
- Stator resistance, self and mutual inductance of all phases are equal and constant.
- Hysteresis and eddy current losses are eliminated.
- All semiconductor switches are ideal.

The electrical and mechanical mathematical equations of BLDC are:

Voltage equations:

$$V_a = Ri_a + (L - M) \frac{di_a}{dt} + E_a \quad (1)$$

$$V_b = Ri_b + (L - M) \frac{di_b}{dt} + E_b \quad (2)$$

$$V_c = Ri_c + (L - M) \frac{di_c}{dt} + E_c \quad (3)$$

EMF equations:

$$E_a = K_e \omega_m F(\theta_e) \quad (4)$$

$$E_b = K_e \omega_m F\left(\theta_e - \frac{2\pi}{3}\right) \quad (5)$$

$$E_c = K_e \omega_m F\left(\theta_e + \frac{2\pi}{3}\right) \quad (6)$$

Torque equations:

$$T_a = K_t i_a F(\theta_e) \quad (7)$$

$$T_b = K_t i_b F\left(\theta_e - \frac{2\pi}{3}\right) \quad (8)$$

$$T_c = K_t i_c F\left(\theta_e + \frac{2\pi}{3}\right) \quad (9)$$

$$T_e = T_a + T_b + T_c \quad (10)$$

$$T_e - T_l = J \frac{d^2\theta}{dt} + B \frac{d\theta}{dt} \quad (11)$$

Where , k=a,b,c

$V_k$  - Phase voltage applied from inverter to BLDC

$i_k$  -Phase current

M -Mutual inductance

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Vol. 7, Issue 4, April 2018

- L -Inductance of each phase of BLDC
- R -Resistance of each phase of BLDC
- $T_e$  -Electric torque produced by BLDC
- $T_k$  -Electric torque produced by  $k_{th}$  phase
- $K_t$  -Torque constant
- $K_e$  -Back - EMF constant
- $E_k$  -Phase back - EMF
- $F(\theta)$  -Back - EMF reference as function of rotor position
- $\theta_c$  -Electrical angle of rotor
- $\omega_m$  -Angular speed of rotor

The state space form of equations (1), (2), (3) and (11) can be derived as:

$$V_{ab} = R(i_a - i_b) + (L - M) \frac{d}{dt} ((i_a - i_b) + E_{ab}) \quad (12)$$

$$V_{bc} = R(i_b - i_c) + (L - M) \frac{d}{dt} (i_b - i_c) + E_{bc} \quad (13)$$

Where,  $i_a+i_b+i_c=0$ , therefore modifying the equations (12) and (13) and neglecting the mutual inductance the phase current  $i_a$  and  $i_b$  can be written as,

$$i_a = \int \frac{1}{3L} (-3Ri_a + 2V_{ab} + V_{bc} - 2E_a + E_b + E_c) \quad (14)$$

$$i_b = \int \frac{1}{3L} (-3Ri_b - V_{ab} + V_{bc} + E_a - 2E_b + E_c) \quad (15)$$

### III. OVERALL SYSTEM MODEL

The structure of the control strategy system is shown in Fig.1. Through the pedal, we can obtain the driver's required braking force. The front brake force, state of charge of the battery (SOC), state of charge of the supercapacitor, and

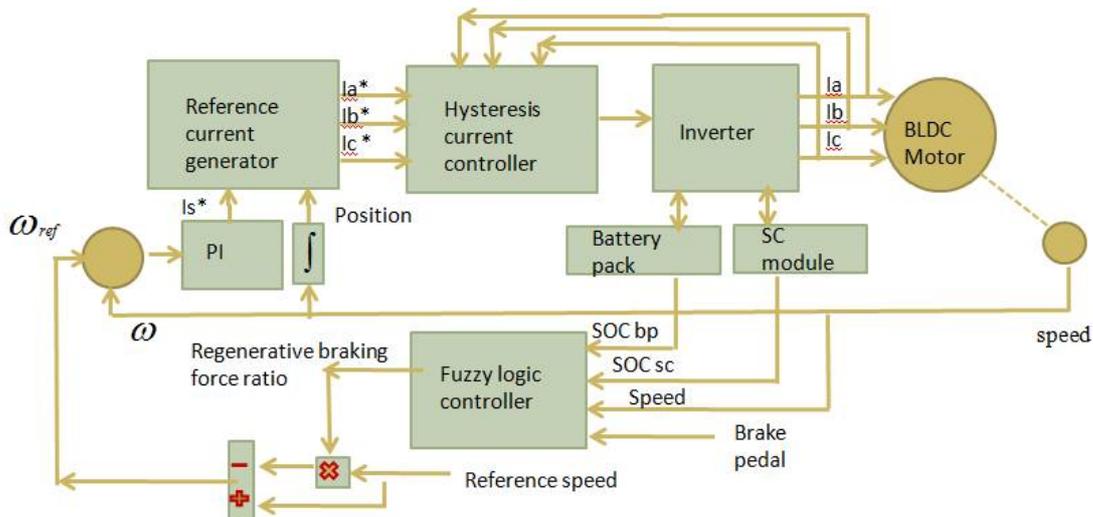


Fig: 1 Structure of the control strategy system

speed of the BLDC motor is given as the input to the fuzzy logic controller. From the fuzzy logic controller, we can obtain a ratio proportional to the value of the regenerative braking force. Multiplying this value with the reference speed and calculate the difference of this value with the reference speed we will obtain the controlled reference speed. This controlled reference speed is compared with the actual speed of the BLDC motor and the error is tuned with a PI controller.

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Vol. 7, Issue 4, April 2018

### IV. HYSTERESIS CURRENT CONTROLLER

The Hysteresis current controller contributes to the generation of the switching signals for the inverter. Hysteresis-band PWM is an instantaneous feedback current control method of PWM where the actual current continually tracks the command current within hysteresis-band. The control circuit generates the reference current and it is compared with actual phase current wave. When the current exceeds upper band limit, the upper switch is off and lower switch is on. As the current exceeds lower band limit, upper switch is on and lower switch is off. Thus, the actual current is always limited within a hysteresis band [5].

- If  $\Delta I_a > H$ , Q1 is off and Q2 is on.
- If  $\Delta I_a < L$ , Q1 is on and Q2 is off.
- If  $\Delta I_b > H$ , Q3 is off and Q4 is on.
- If  $\Delta I_b < L$ , Q3 is on and Q4 is off.
- If  $\Delta I_c > H$ , Q5 is off and Q6 is on.
- If  $\Delta I_c < L$ , Q5 is on and Q6 is off.

### V. FUZZY LOGIC CONTROLLER

Braking force distribution in EVs with regeneration is influenced by many factors, and many parameters are constantly changing, so recycling strategy is difficult to be expressed. The fuzzy logic control strategy for EV braking force distribution can be easily demonstrated by the influence of different factors. Therefore, the fuzzy control theory is applied to the EV braking force distribution [6]. The fuzzy control strategy of the EV braking force distribution structure is shown in Fig. 1; the four inputs are the EV front-wheel braking force, speed, and battery charge state [state of charge (SOC)] and state of charge of super capacitor. In the fuzzy control system, the input variables include the front braking force, the SOC of battery and super capacitor, and the EV speed. The output variable is the ratio which is proportional to the regenerative braking force taking in the front braking force.

Front braking force: the driver braking requirements are concerned with the driving safety. The value of the braking force represents the braking distance and time the driver requires. We prefer the concourse of speed to be low, middle, and high, and the universe of discourse is [0, 2000]. [6]. Fig 2: (c) shows the membership function of speed.

SOC of super capacitor: when the battery's SOC is less than 10%, the internal resistance of the battery is high, unsuitable charging in this case; the regenerative braking force should be a smaller proportion. When the SOC is between 10% and 90%, the battery can be charging with a large current; the ratio of the regenerative braking force should be correspondingly increased. When the SOC is greater than 90%, the charging current should be reduced to prevent the excessive charging of the battery; the value of the regenerative braking force should be lower. We prefer the set of SOC to be low, middle, and high, and the universe of discourse is [0, 1]. [6]. Fig: 2 (d) shows the membership function of SOC of supercapacitor.

SOC battery: SOC of the battery remains within the safe margin. We prefer the set of SOC to be low, middle, and high, and the universe of discourse is [0, 1]. Fig: 2 (b) shows the membership function of SOC of battery pack.

Speed: vehicle speed plays an important role in ensuring the brake safety. To ensure the brake safety and to comply with the relevant legislation, the regenerative braking force should be a low proportion when the speed is low. When speed is high, we can increase the ratio of the regenerative braking force to the biggest value. We prefer the set of speed to be low and high, and the universe of discourse is [0, 500]. The membership functions can be seen in Fig. 2(c).

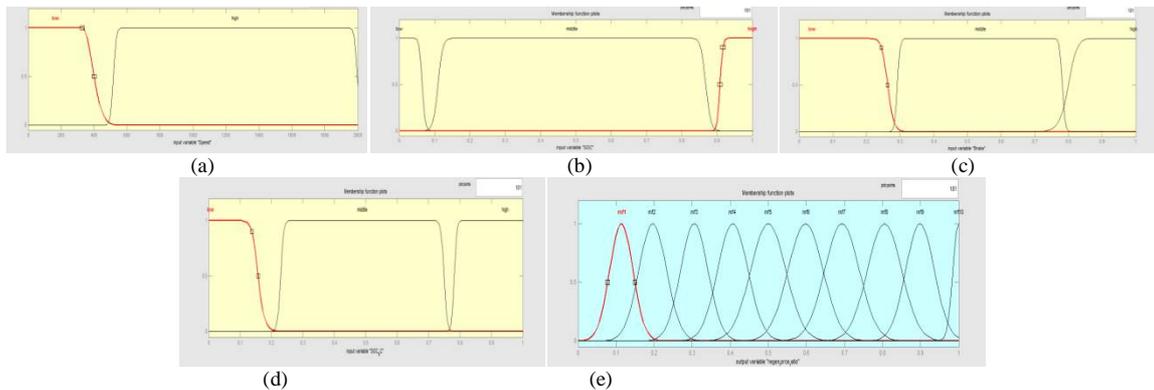
Output variables: the type of the fuzzy logic controller is Mamdani. Ratio = {MF1, MF2, MF3, MF4, MF5, MF6, MF7, MF8, MF9, MF10} = (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0). The membership functions can be seen in Fig. 2(e). Fuzzy linguistic variables are: the front braking force is L, M, and H; SOC is L, M, and H; and speed is L and H. We prefer the rules shown in Table 1.

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Vol. 7, Issue 4, April 2018



The membership functions are Fig. 2. Membership functions of fuzzy control. (a) Membership function of the speed (b) Membership function of the SOC of the battery pack (c) Membership function brake. (d) Membership function of SOC of supercapacitor (e) Membership function of SOC of ratio.

TABLE 1: Fuzzy logic control rules

Speed	SOC SC	SOC Battery	F <sub>front</sub>	MF	Speed	SOC SC	SOC Battery	F <sub>front</sub>	MF
L	L	L	L	1	H	L	L	L	3
L	M	M	M	2	H	M	M	M	5
L	H	H	H	3	H	H	H	H	7
L	L	L	L	2	H	L	L	L	5
L	M	M	M	4	H	M	M	M	6
L	H	H	H	5	H	H	H	H	7
L	L	L	L	4	H	L	L	L	5
L	M	M	M	5	H	M	M	M	7
L	H	H	H	6	H	H	H	H	9

Fuzzy controller rule is built based on the above descriptions. And the membership functions where plotted on the fuzzy controller.

## VI. PROPORTIONAL–INTEGRAL (PI) CONTROL

Closed loop control is achieved with PI Controller. Main function of the PI controller is the regulation of speed. Value of  $K_p$  and  $K_i$  are determined by Ziegler Nichols Tuning method.

$$G(S) = \frac{1}{k_e} \frac{1}{\tau_m \tau_e s^2 + \tau_m s + 1} \quad (16)$$

$$G(S) = \frac{0.565}{1.343 \times 10^{-5} s^2 + 0.01363 s + 1} \quad (17)$$

Where  $\tau_m$ ,  $\tau_e$  are the mechanical and electrical times constant. Solving the characteristic equation of closed loop system and using Routh Hurwitz Criteria obtained the critical gain and critical period,  $K_{cr} = 1.7699$  and  $P_{cr} = .01636$ . Substituting  $K_{cr}$  and  $P_{cr}$  obtained the gain values of the PL speed controller,  $K_p = 0.796$   $K_i = 58$ .

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Vol. 7, Issue 4, April 2018

## VII. SIMULATION RESULTS

Four quadrant operation of BLDC motor is shown in fig.3. without the hysteresis current controller. The resultant torque graph shows increased ripples.

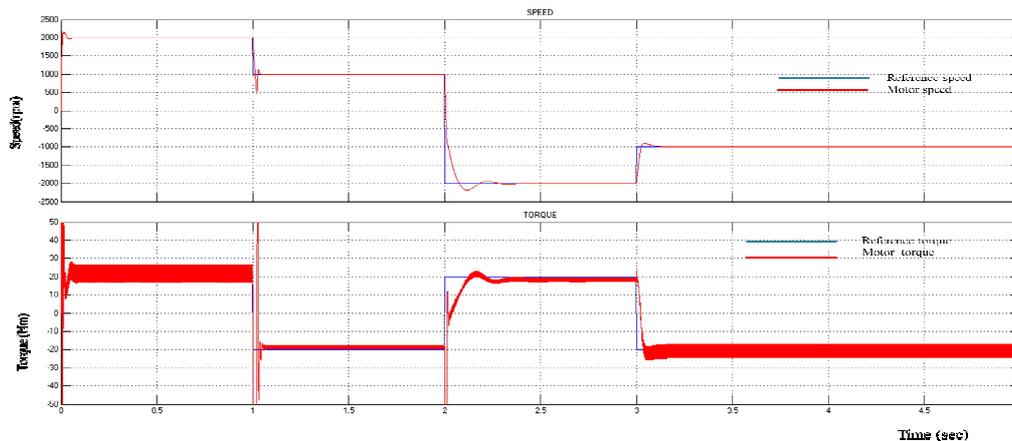


Fig 3: Four quadrant operation of BLDC motor without hysteresis current controller.

Fig.4. shows the four quadrant operation of BLDC motor. here the torque ripples are reduced by the use of current controller.

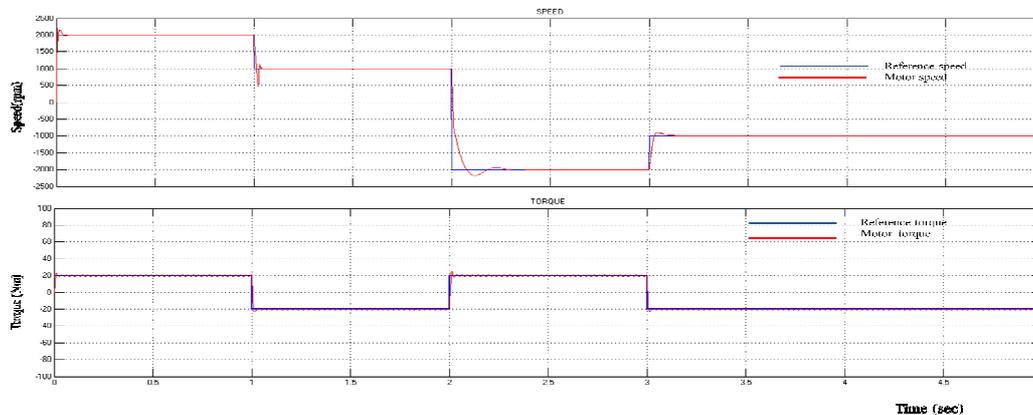


Fig 4: Four quadrant operation of BLDC motor with hysteresis current controller.

Fuzzy logic controller is implemented to predict the regenerative braking force. The ratio which is proportional to regenerative braking force will determine the controlled reference speed that an EV to track when a brake pedal is given. Fig.5. show the speed case when the reference speed is 1500rpm and 50% brake is applied at 0.7sec. Before the application of brake the brake force ratio was 0.41, after 0.7 sec the brake force ratio is 0.83. And the corresponding controlled reference speed is, before 0.7 sec 885rpm and after 0.7sec 255rpm. The initial SOC of the battery was 80% and initial SOC of supercapacitor is 77%. The SOC of super capacitor is showing a gradual increases and the SOC of battery is maintained to 80 %. After 3 sec SOC of battery is also increasing.

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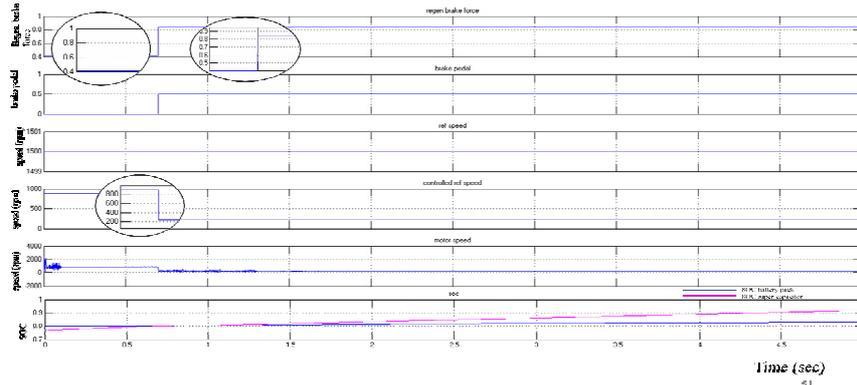


Fig 5: Case: 1 when the reference speed is 1500rpm

Fig.6. show the speed case when the reference speed is 500rpm and 30% brake is applied at 0.7sec. Before the application of brake the brake force ratio was 0.37, after 0.7 sec the brake force ratio is 0.62. And the corresponding controlled reference speed is before 0.7 sec, 315 rpm and after 0.7sec, 190rpm. The initial SOC of the battery was 80%. After 0.7 sec the SOC of battery was maintained to 80 %. SOC of super capacitor is gradually increasing after the application of brake.

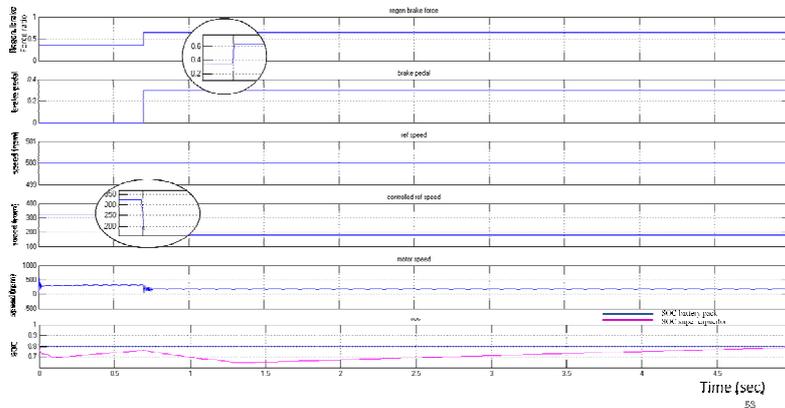


Fig 6: Case: 2 when the reference speed is 500rpm

Table 2: Motor specifications

Description	Value
Rated voltage	72 V
Rated speed	2000rpm
Rated power	5kw
Number of poles	8
Back EMF constant	0.175 v/(rad/sec)
Inductance	0.0085Mh
Resistance	2.875 Ω
Moment of inertia J	$0.8 \times 10^{-3} \text{ Kg m}^2$
Frictional factor B	$1 \times 10^{-3} \text{ Nm.s / rad}$

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Vol. 7, Issue 4, April 2018

Table 3: Battery specifications

Battery Parameter	value	Supercapacitor Parameter	Value
Nominal voltage	80V	Rated voltage	77V
Rated current	25Ah	No: of series capacitor	24
Battery pack	Lead acid battery	No: of parallel capacitor	6
SOC	80%	SOC	77%

Table 2. gives the specification of BLDC motor and the battery specification of the hybrid energy storage system (HESS) are given in the table 3.

## VIII. CONCLUSION

In this paper Fuzzy controller based efficient brake force prediction with hybrid energy storage system (HESS) in regenerative braking system is proposed. BLDC motor is modelled along with the regenerative braking system and controllers in SIMULINK. The four quadrant operation of BLDC motor is designed and the simulation results were found satisfactory. Torque ripples were reduced with the help of hysteresis current controller. Improved the charging efficiency of the regenerative system. Thus, a new regenerative braking system for EVs with HESS and driven by BLDC motor is proposed and simulated, and the simulation results were found satisfactory.

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