

Fuzzy Based Energy Management Scheme for Electric Vehicle with Hybrid Energy Storage System

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ABSTRACT

The efficiency and durability of Electric Vehicle (EV) batteries are significantly influenced by factors such as peak power demands, commuting patterns, and charge transfer frequency. The effectiveness of Energy Management Schemes (EMS) is crucial in determining the range and efficiency of EVs. Hybrid Energy Storage Systems (HESS) have garnered considerable attention in EV research due to their ability to complement each other in terms of energy dissipation and charging characteristics, making them ideal for EV applications. This study introduces a hybrid system integrating both a battery and an ultra-capacitor (UC) to control a Permanent Magnet Synchronous Motor (PMSM)-driven EV. The ultra-capacitor acts as a power buffer during acceleration and deceleration, reducing strain on the battery and enhancing longevity and safety. Through appropriate inverter switching, the PMSM can harvest regenerative power during braking and downhill drives. Charge storage priority is given to the ultra-capacitor, which then supplies power for vehicle acceleration, effectively minimizing strain on the battery during peak power demand periods. Additionally, a Fuzzy Logic Controller (FLC) is utilized to manage force distribution during braking. Simulation studies conducted in MATLAB confirm the effectiveness of the proposed energy management strategy, and experimental verification further validates its efficacy.

Keywords: HESS; Energy Management Scheme; Super capacitor; Electric vehicle; Fuzzy Logic Controller

1. INTRODUCTION

With the depletion of traditional drivetrain fuel sources and the growing demand for eco-friendly alternatives, there is a significant need for innovative and sustainable solutions. EVs have emerged as environmentally conscious options with zero emissions. Compared to traditional Internal Combustion (IC) engines, EVs offer benefits such as quicker response times, increased efficiency, and enhanced controllability. Due to their widespread acceptance and impressive performance, EVs are closely monitored by both the market and research communities. A wealth of literature exists, covering various aspects of EVs including their design, technologies, range, challenges, charging strategies, and other considerations [1-3].

Hybrid Electric Vehicles (HEVs) incorporate an additional drivetrain, either in series or parallel, which sets them apart from the battery-only configuration of All-Electric Vehicles (AEVs). Plug-in HEVs enable recharging from an external source. Among battery options for EVs, Lithium-ion batteries are favoured for their durability, high power/energy density, and environmentally friendly attributes, surpassing Ni-Cd, Lead-acid, and Ni-MH batteries [4].

Relying solely on a single energy storage system in an EV can lead to driver anxiety regarding range limitations during a journey. Depending solely on a single battery may result in challenges such as low power density, reduced lifespan, and high size/cycle costs [5]. To address such concerns, integrating an additional rechargeable source serves as a backup, alleviating stress on the battery and enhancing overall efficiency [6-8].

While a hybrid system typically combines a conventional internal combustion engine with an electric

motor, this setup requires the use of fossil fuels and increases overall bulkiness. In contrast, supercapacitors offer both the storage capacity of a battery and the rapid discharging characteristics of a capacitor. These double-layer electric capacitors exhibit high power density and an extended lifecycle. However, their lower energy density limits their effectiveness as a standalone storage solution. Nonetheless, their fast charging and discharging rates make them ideal components for a HESS, complementing a battery. Despite their lower voltage per cell, supercapacitors are user-friendly [9-11]. The integration of a battery and supercapacitor combination proves effective in meeting peak power demands while efficiently storing regenerative energy during driving.

The choice of electric motor utilized in propulsion, its control method, and the power electronics involved are pivotal factors influencing both the cost and performance of the system. Among the options for EVs, Induction motors [12], Brushless DC motors (BLDC), and PMSM are all viable selections. Although controlling PMSM drives presents challenges, they are extensively employed in various applications including industrial, robotic, household, and automotive sectors, particularly well-suited for regeneration purposes. Besides motor selection, the effectiveness of charging strategies and power conversion topologies is equally crucial [13-15]. Bidirectional converters (BDC) facilitate the bidirectional flow of power between the source and the motor. The choice of converter and technology is contingent upon factors such as power demand, frequency of charging/discharge cycles, and the availability of power sources.

Incorporating an ultra-capacitor into the EV setup can help mitigate strain on the battery. Essential for effectively managing power transfer between the source and the load is the presence of a controller and a control

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algorithm. The decision between programmable and heuristic controllers is influenced by factors such as the drive cycle and the State of Charge (SoC) of the battery. Control strategies play a critical role in distributing and guiding power among various components [16-18]. FLCs demonstrate versatile applications in power electronic control systems, as evidenced by previous research [19-20]. Controllers function based on either rule-based or optimization-based principles [21-22], and fuzzy-based controllers provide flexibility within the control domain of the system.

In this paper, a control strategy for a HESS comprising a battery and an ultra-capacitor is presented, employing an FLC. The EMS is devised to oversee the SoC of both the battery and ultra-capacitor, aiming to stabilize battery characteristics. The FLC not only drives the motor forward but also facilitates the return of regenerative power to the battery/ultra-capacitor as needed. Leveraging converter switches and motor inductance, the controller efficiently handles the reverse power flow. The following sections will present simulation studies and experimental validation of the HESS utilizing ultra-capacitor.

2. HYBRID ENERGY STORAGE SYSTEM

The FLC has to allocate the power flow between different components of the HESS according to the operating conditions. Figure 1 represents the schematic block of the system under consideration. The HESS consists of a battery and an ultra-capacitor along with a bidirectional converter. The HESS feeds the inverter whose output depends on the commands from the FLC.

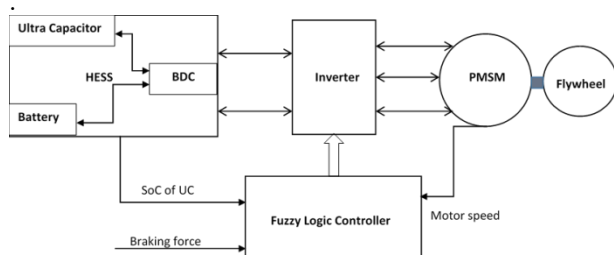


Figure 1. Block Schematic of the HESS for PMSM control

There are three inputs for the FLC, speed/position of the motor, state of charge of the ultra-capacitor and the braking force. The inverter is able to feed the PMSM as well as allow the flow of regenerative current back to the HESS with proper switching and utilizing the motor inductance. PMSM has an attached flywheel for keeping up the angular momentum to extend the regeneration period. During acceleration, in order to support the battery and to reduce its stress, ultra-capacitor delivers to the load. The fast response of ultra-capacitor make it suitable for storing the regenerative energy during the very small periods of regeneration. Figure 2 shows the circuit diagram for the HESS utilizing battery and super capacitor.

. There are 4 modes of operation for this circuit. Figure 3 shows the modes of operation. In mode 1 (figure 3.a) motor requires power less than or equal to that of the battery. The battery alone supplies the motor through the inverter. Hall sensors in the PMSM feedback the position information to the controller and generate necessary signals for electronic commutation. Diode D1 remains reverse biased, super capacitor is idle and buck converter is in OFF state.

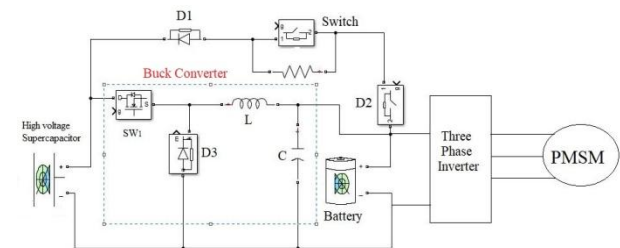
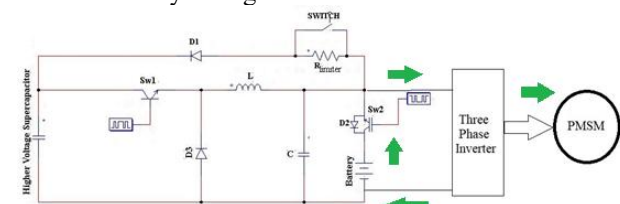
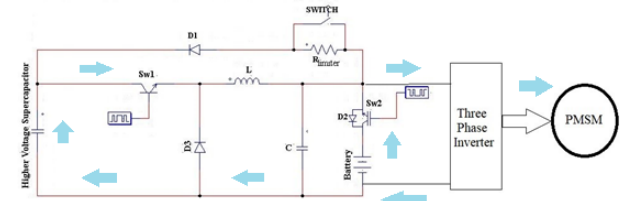


Figure 2. Circuit Diagram for the HESS

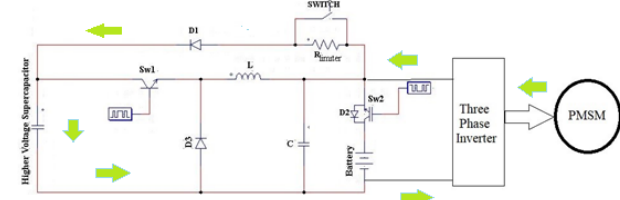
In mode 2 (figure 3.b) the vehicle is in acceleration mode, where the motor requires additional power. The controller turns the buck converter on so that energy stored in the super capacitor is available for the inverter terminals. Super capacitor voltage is higher than the battery voltage.



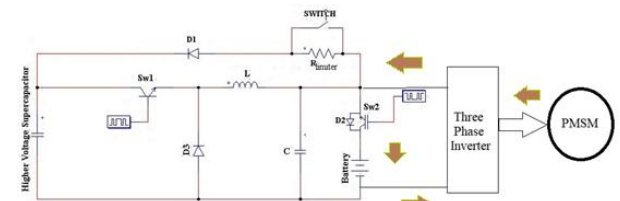
1.a Mode 1



2.b Mode 2



3.c Mode 3



4.d Mode 4

Figure 3. Modes of operation of the HESS

. Hence, buck operation ensures that battery charging occurs at its nominal voltage and power is available at the dc link. The converter duty ratio controls the power flow from super capacitor to the motor through the inverter. The ability to handle the transient power makes super capacitor a good choice for assisting the battery.

In the third mode of operation (figure 3.c), regeneration occurs. Appropriate switching of the inverter switches allows the regenerative power to boost up the dc link voltage. As D1 is forward biased, the super capacitor module gets charged. As inductance of the motor comes in series with the circuit, it does not require additional dc-dc converter for power transfer. Regeneration occurs when the vehicle is going downhill or braking occurs. Regeneration not only assists in braking but also provides energy feedback.

3. CONTROL STRATEGY

P_m and $P_{battery}$ represent the power of motor and battery respectively. V_{SC} , $V_{SC, min}$ and $V_{SC, max}$ stand for the voltage in the super capacitor, its minimum value and maximum value. As mentioned in the previous section, there are four modes of operation depending on the available battery power, required motor output and the state of charge of battery and the ultra capacitor. When the output power requirement is below the battery power, the vehicle operates in the normal mode. Super capacitor supplies accelerating power when the required power is greater than the battery power and super capacitor voltage is greater than both its minimum value and battery voltage.

Comparison of V_{SC} and $V_{SC, max}$ determines the regeneration power flow. If the former is less than the latter, regeneration charges super capacitor. Else, battery stores the regeneration power. The variations in input and output power flow necessitates choice between different modes of operation. Figure 4 shows the flow chart for the control strategy

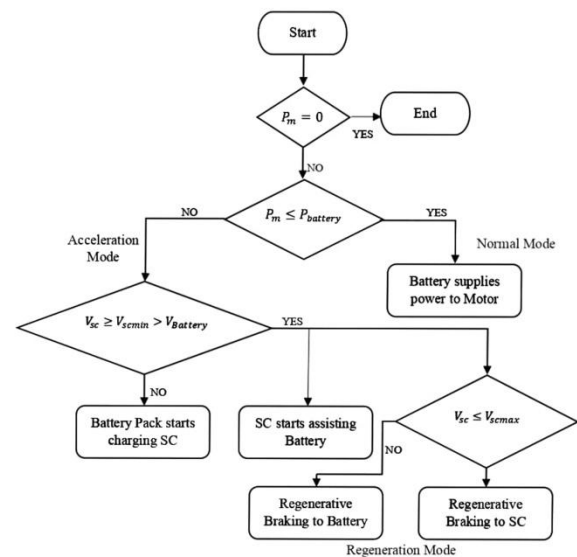


Figure 4. Flowchart of the control strategy

Table 1 explains the modes of operation and the path followed by the motor current during the four modes of operation. For example, during the vehicle normal mode, the power flows from battery through switch SW2 towards the inverter to drive the PMSM.

Modes	Conditions	Path followed
Vehicle Normal Mode	$P_{motor} \leq P_{battery\ rated}$	Battery→SW2→Inverter→PMSM
Vehicle Acceleration Mode	$P_{motor} \geq P_{battery\ rated}$	Battery→SW2→Inverter→PMSM
	$V_{SC} \geq V_{SC\ min}$	UC→SW1→L→Inverter→PMSM
	$V_{SC} > V_{battery}$	
Regeneration with Super capacitor	$V_{SC} \leq V_{SC\ max}$	PMSM→Inverter→D1→SC
Regeneration to Battery	$V_{SC} \geq V_{SC\ max}$	PMSM→Inverter→D2→Battery

Table 1. Vehicle modes and operation

3.1 Fuzzy Logic Controller

The FLC determines the braking force distribution between the front and rear wheels. The factors that affect braking force distribution are the available Braking force, SoC of the super capacitor and the speed of the motor. Hence, the input variables (figure

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5) for the FLC are Braking force (F_{front}), SoC of ultra-capacitor (SOC) and the motor speed (Speed).

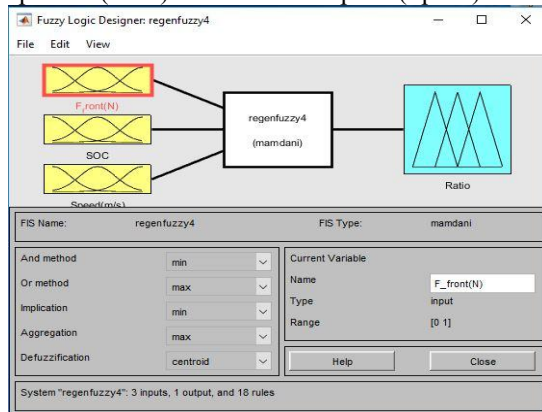


Figure 5. Structure of the FLC

Membership functions for the input and output are available in figure 6. The values of braking force can indicate both the braking distance and the time needed for the driver to stop the vehicle. For example, a high braking force signifies the need for immediate stopping of the vehicle (MF1). In such circumstances, the proportion of regenerative braking force should be decreased. When the braking force is moderate, the ratio of regenerative braking force can be raised. Moreover, when the braking force is low, a substantial regenerative braking force can be employed to maximize energy recycling.

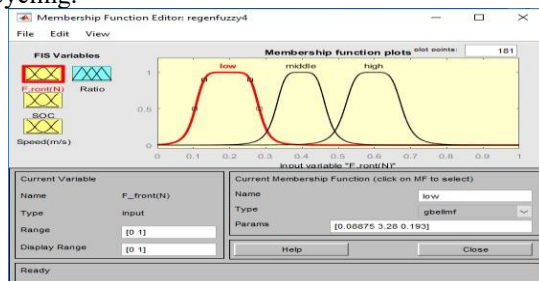


Figure 6.a Braking force

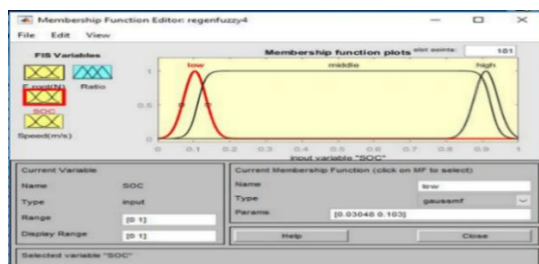


Figure 6.b SoC of ultra-capacitor

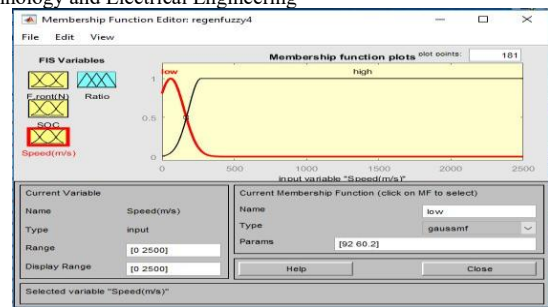


Figure 6.c Motor Speed

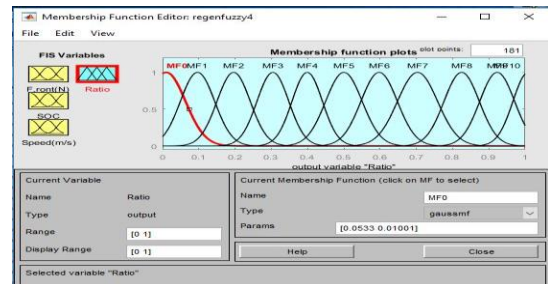


Figure 6.a Braking force distribution

Figure 6 Membership functions for input and output

The braking force (figure 6.a) has a gauss-bell variation with 3 regions, low (< 0.3), medium ($0.3-0.5$) and high (> 0.5). The range allowed is between zero and one. When the SoC drops below 10%, the internal resistance of the battery increases significantly. During this period, it is not advisable to charge the battery, thus the regenerative braking force should be kept low. As the SoC ranges between 10% and 90%, the battery can accept charging, allowing for an increase in regenerative braking force accordingly. However, as the SoC exceeds 90%, the charging current should be reduced to prevent lithium ion deposition, necessitating a decrease in regenerative braking force.

The super capacitor SoC (figure 6.b) has a Gaussian variation with three regions, low (< 0.1), medium ($0.1-0.9$) and high (> 0.8). The range is between zero and one. The motor speed (figure 6.c) is either low (< 250 rpm) or high (> 250 rpm). The speed of the vehicle significantly influences braking safety. At low speeds, the regenerative braking force should remain minimal, gradually increasing to an appropriate level for medium speeds. At high speeds, the regenerative braking force is maximized to capture the maximum amount of energy possible. The FLC generates ratio of required brake force distribution (figure 6.d) as the output.

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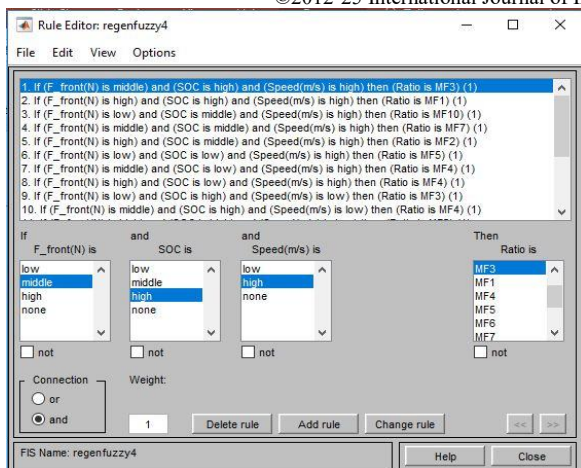


Figure 7. Fuzzy Rule Editor

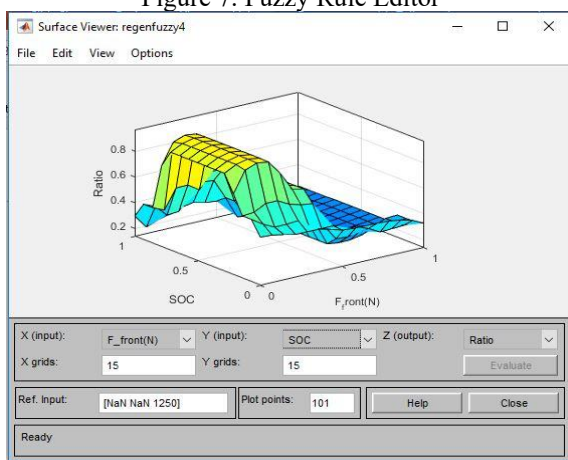


Figure 8. Fuzzy Surface Viewer

Figure 7 shows the rules editor and figure 8 shows the fuzzy surface viewer. Table 2 summarizes the input output relations in the FLC.

The FLCs are recognized for their ability to handle imprecise, uncertain, or variable inputs more adeptly than classical controllers. They excel in managing linguistic variables and vague definitions, which renders them appropriate for systems characterized by ambiguous or non-linear relationships. Additionally, they offer the benefits of simplified implementation, human-like reasoning, non-linear control, and adaptability. Altogether, these advantages position FLCs as ideal choices for applications where precise mathematical modelling proves challenging, or where systems demonstrate non-linear, uncertain, or variable behavior.

Sl. No	Speed of motor	SoC (SC)	Force	Regenerative Braking Force
1	High	High	Low	MF10
2	High	High	Medium	MF3
3	High	High	High	MF1
4	High	Medium	Low	MF10

5	High	Medium	Medium	MF7
6	High	Medium	High	MF2
7	High	Low	Low	MF5
8	High	Low	Medium	MF4
9	High	Low	High	MF4
10	Low	High	Low	MF3
11	Low	High	Medium	MF4
12	Low	High	High	MF2
13	Low	Medium	Low	MF1
14	Low	Medium	Medium	MF4
15	Low	Medium	High	MF5
16	Low	Low	Low	MF3
17	Low	Low	Medium	MF5
18	Low	Low	High	MF5

Table 2. Fuzzy Membership Rules

4. RESULTS AND DISCUSSIONS

Electrical system simulation software like MATLAB/Simulink provides a platform for checking the validity of algorithms and strategies in control problems involving power electronics and drives. A programmable device is required for implementing the controller in real time. DSP (Digital Signal Processor) is used in implementing the strategy in hardware.

4.1 Fuzzy Logic Controller

The Simulink model of the proposed control system involving the PMSM drive, battery, super capacitor and necessary power converters is shown in figure 9. This study is based on the simulation of the energy storage system with a battery and ultra-capacitor for the PMSM motor drive in MATLAB/Simulink. The EMS has a battery (Li ion) as the primary source and a super capacitor as the supplementary source. The model consists of the EMS, FLC controller, the DC-DC converter, the inverter and the PMSM motor. The PMSM motor parameters are; Voltage 300V, Speed 4000 rpm, Power 1.07 kW, Torque 3.6 Nm, Stator resistance 1Ω and L_d and L_q of 0.009 H and 0.024 H respectively. The simulation studies shows the validity of the proposed strategy.

The variation in SoC, current and voltage of battery (figure 10.a) and super capacitor (figure 10.b) are available in figure 10. The vehicle operates in the normal mode till 15 seconds in the graph, where a brake is applied. Regeneration occurs at 15 second on the time line, which affects the characteristics.

Analysis of the supercapacitor voltage, current, and SoC waveforms reveals crucial insights. Until the brake

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application at the initial 15 seconds of simulation time, the supercapacitor current remains at zero, while the voltage and SoC remain constant. Transitioning into regenerative braking mode, the voltage and SoC exhibit an increase, accompanied by a negative current, indicating the supercapacitor's charging process. The motor speed and power are shown in figure 10.c and figure 10.d respectively.

4.2 Hardware implementation.

The simulation model demonstrates that the proposed control strategy is able to drive the motor effectively in different modes of operation. The experimental system consists of a EMS of battery and ultra-capacitor, the dc-dc converter, three phase inverter, PMSM with flywheel and the controller. The controller is built with dsPIC33FJ32MC202. The DSP contains an extensive digital signal processor with a 16 bit micro controller architecture. It supports 2 PWM modules that are 6-channel and 2-channel respectively. Employing DSP as a controller offers efficient, flexible, and precise control capabilities, rendering it suitable for a diverse array of real-time applications.

DC-DC converter

Input Voltage, $V_d = 24V$

Output Voltage, $V_o = 18V$

Duty ratio, $D = 0.75$

Output Power, $P = 0.13kW$

Therefore, output current $I_o = 7.22A$

$$L = V_{in} * D(1 - D) * \frac{T}{\Delta I_o} = 105mH$$

$$C = V_{in} * D(1 - D) * T^2 \frac{1}{8 * L * \Delta V_o} = 840\mu F \text{ Take } 1000\mu F$$

Design of inductor

Selected Core T-27 : Yellow Colour

So, Outer Diameter=7.11mm, Inner Diameter=3.84mm, Height =3.25mm and $L = 105mH$. Therefore, $N = 44$ turns. Figure 11 shows the converter and inverter circuits.

Design of Flywheel

The duration power available for regeneration modifies the energy storage characteristics of the system. With a load like EV, the inertia of the system does not allow the energy to dissipate away. For the prototype implementation, in order to harvest the regenerative energy, a flywheel is necessary. Flywheels offer a multitude of advantages including energy storage, stabilization, energy recovery, power transmission, and motion control. These attributes render them versatile components suitable for a broad spectrum of mechanical and electromechanical systems.

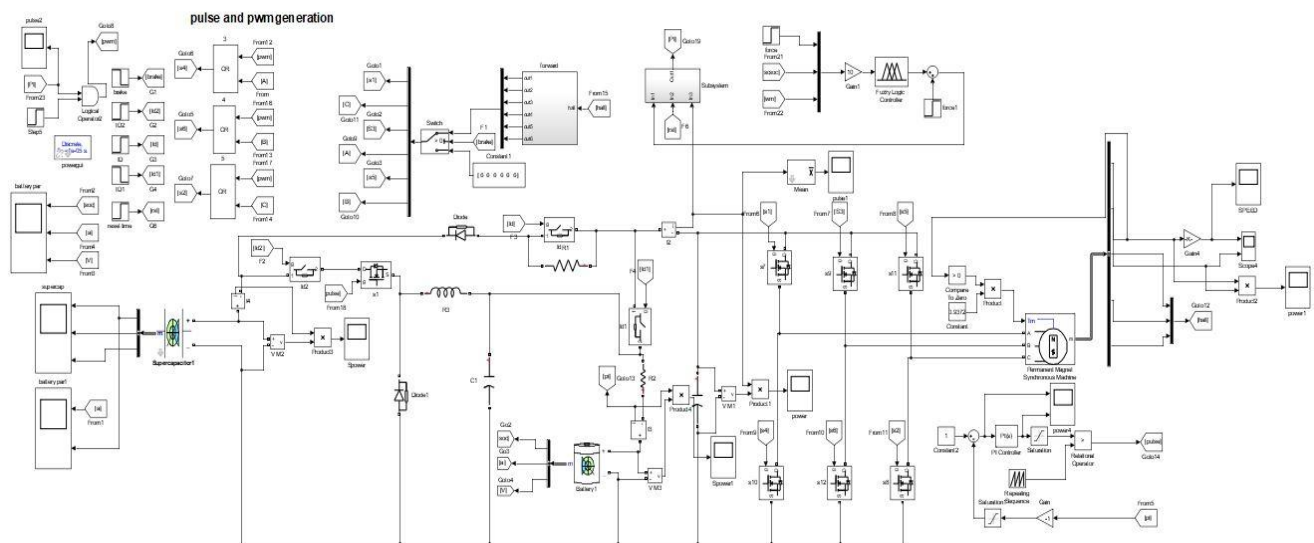


Figure 9. Simulink diagram for the HESS

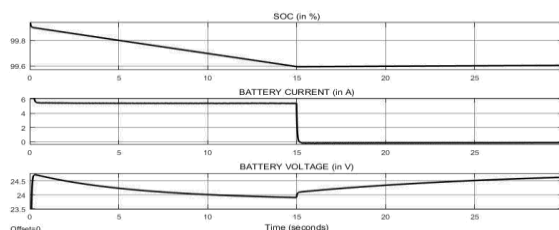


Figure 10.a SoC, current and voltage of battery

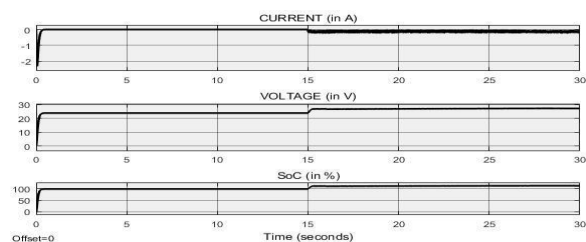


Figure 10.b SoC, current and voltage of SC

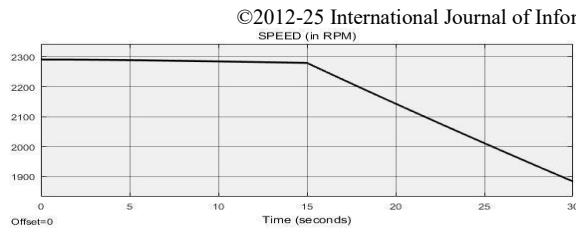


Figure 10.c Speed of the motor

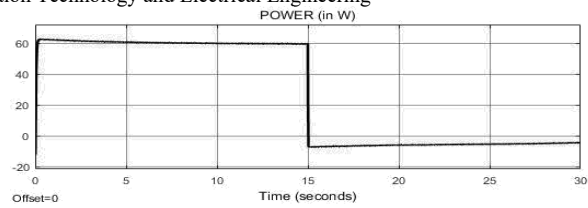
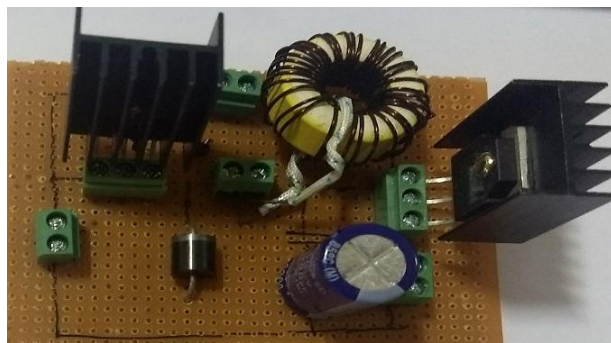
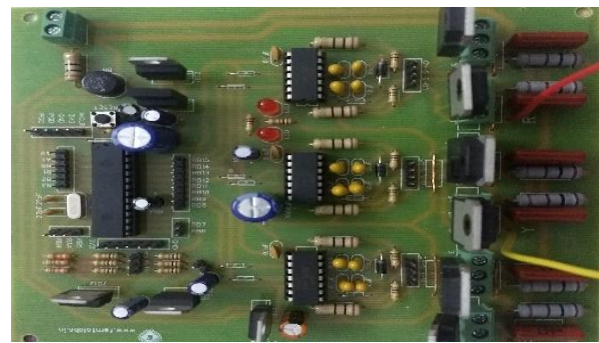


Figure 10.d Power developed

Figure 10. Performance characteristics



(a)



(b)

Figure 11. DC-DC converter (a) and Inverter with dsPIC dsPIC33FJ32MC202 (b)

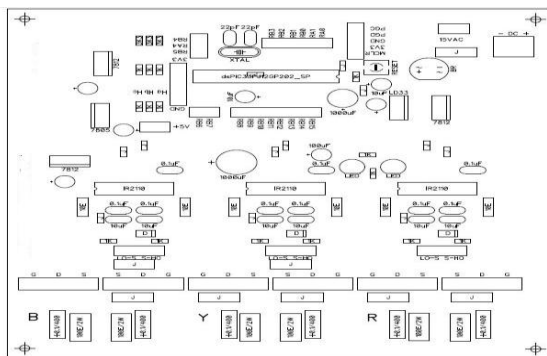


Figure 12. PCB Layout

Electrical Design

Time to achieve full speed at rated voltage = 5sec

Maximum angular speed, $\omega = 2 * \pi * \frac{8000}{60} = 837.75$ rad/sec

Maximum torque of the motor = 0.18 Nm

Torque eqn. of the motor, $T = \frac{Jd\omega}{dt} + B\omega$

Therefore, $J = 0.00112 \text{ Kg-m}^2$

As, $J = \frac{1}{2} mr^2$, radius of 8cm and 0.350kg can be selected

Mechanical Design

$$\frac{1}{2} m(a^2 + b^2) = J = 0.00112 \text{ Kg-m}^2$$

By software iteration, $a = 9\text{cm}$, $b = 3\text{cm}$ (; a is the outer radius and b is the inner radius of the flywheel)

Hence, $m = 0.3\text{kg}$

Selection of super capacitor

Moment of inertia of the flywheel

$$= \frac{1}{2} * 0.35 * (0.08)^2 = 0.00112 \text{ Kg-m}^2$$

Maximum Kinetic energy stored in the flywheel at

$$8000\text{rpm} = \frac{1}{2} * J * (\omega)^2 = 393 \text{ J}$$

$$\text{Energy to be stored in super capacitor} = \frac{1}{2} * CV^2 = 393 \text{ J}$$

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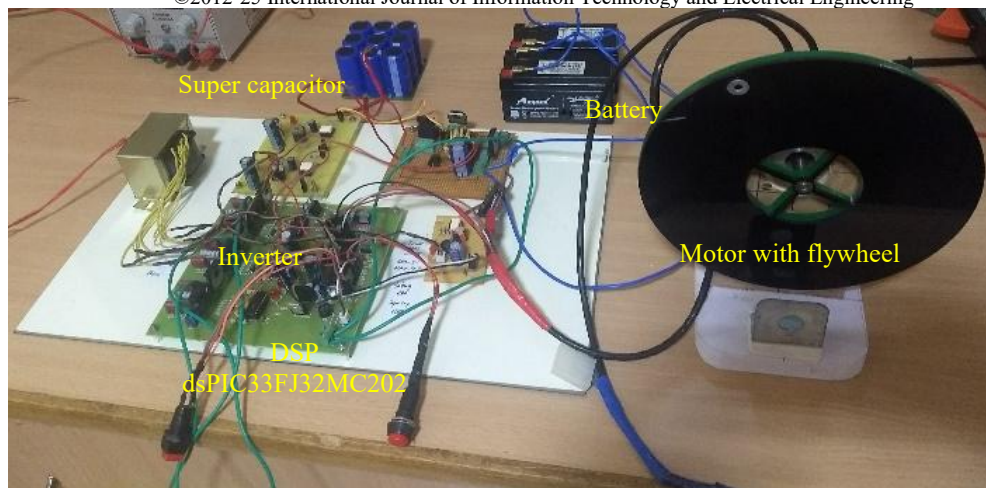


Figure 13. Hardware implementation

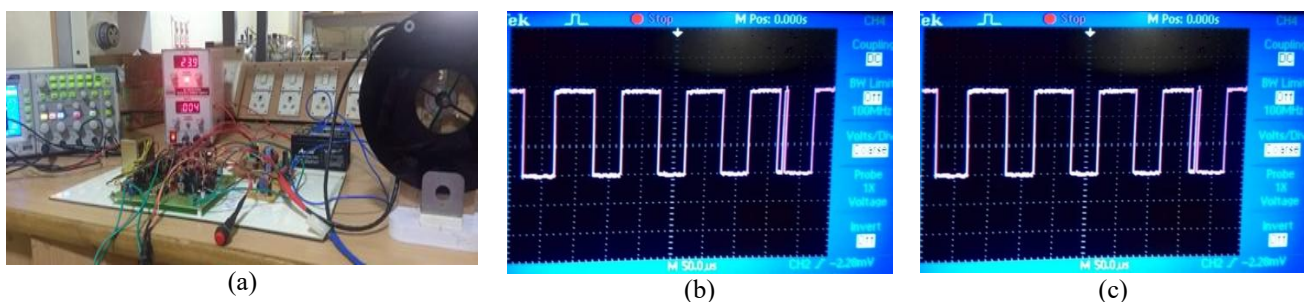


Figure 14 (a) Hardware and DC link voltages (b) normal mode, (c) acceleration mode

Therefore, a SC with 2.7 V, 107F is selected. Hall effect sensors are commonly employed for speed measurement in motors, especially BLDC and PMSM variants. Positioned near the motor's rotating part, they detect a magnet fixed to the shaft, generating voltage pulses as it rotates. Pulse frequency directly corresponds to motor speed.

Typically, the sensor output is digital, with each pulse representing a full motor revolution. This digital signal can interface with microcontrollers or other digital devices for processing and determining speed. Figure 12 shows the PCB layout for the proposed system drawn in Diptrace software and figure 13 shows the circuit implementation. The experimental validation and the dc link voltages are shown in figure 14.

4 CONCLUSION

This paper delves into the operational principle, control algorithm, and deployment of an EMS tailored for applications such as EVs. The system integrates a PMSM drive powered primarily by a battery, with a supercapacitor serving as an auxiliary source. The supercapacitor demonstrates superior transient power capabilities compared to the battery, leading to improved regeneration and control compared to an EV reliant solely on battery power.

In order to facilitate bidirectional power flow, the incorporation of a bidirectional converter is imperative, bolstering the EMS's storage capacity. Operating across a wide spectrum of conditions, the FLC

lends an intelligent dimension to the system, enhancing its regeneration capabilities. Simulations in MATLAB/Simulink authenticate the proposed approach, with the controller execution executed via DSP. Integrating a flywheel ensures efficient harnessing of regenerated energy, fostering energy preservation and mitigating equipment wear. Despite cost considerations, PMSM drives emerge as optimal selections for EVs due to their proficient regeneration capabilities. This paper additionally addresses the modeling, simulation, and analysis of the PMSM within the HESS. The reduction in peak battery currents translates to diminished average on-state conduction losses and reduces the rating requirements of the corresponding switches, consequently enhancing battery longevity and overall efficiency. Further the power split strategies can be used for other drive motors like BLDC and laboratory scale implementation extended to practical applications.

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