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A regulatory power split strategy for energy management with battery and ultracapacitor

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ABSTRACT

Electric vehicle batteries face fast degradation due to the high frequency of charging/discharging cycles and great peak power demands. Lifetime, continuity of supply and power density of these batteries affect the performance of electric vehicles (EVs). Hybrid energy storage systems (HESS) offers a feasible solution by incorporating other energy storage elements like ultra-capacitor (UC) along with battery. Their combination provides higher efficiency and better performance in terms energy/power density. UC can behave like a power buffer when the EV is accelerating and regenerating. The HESS needs a controller that can split the available power between different sub systems as per demand. This paper presents a regulatory control strategy useful in HESS with battery and UC for the speed regulation of a brushless DC (BLDC) motor using a 3-port bidirectional DC-DC converter. The regulatory control strategy monitors the state of charge (SOC) of UC and a fuzzy logic controller regulates the power flow between HESS and the motor. Simulation in MATLAB validates the efficacy of the strategy. Simulation results and hardware evaluation confirm that the regulatory control scheme is effective in splitting the available power according to the load demand and achieves better energy efficiency.

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1. INTRODUCTION

The appeal for energy increases day by day and the deteriorating stock of conventional fuel demands contemporary techniques for drive trains. Electric vehicles offer ecofriendly solutions with almost zero emissions. EVs were in use since 1890s. Considering longer periods, EVs are not only cost effective, but also provides better wheel-to-wheel efficiency, quick response, and ease of control. Hence, EVs are trendsetters not only in market but also among the research community across the globe. Significant amount of research and literature are available regarding EVS [1]–[4]. They deal the architecture of EVs, technologies, integration with the grid, range and range prediction problems, challenges and scope. All electric vehicle (AEV) has the battery alone as the source while hybrid electric vehicle (HEV) has another drive parallel or series with the battery. If the batteries are rechargeable from an external source, they are plug-in hybrid electric vehicle (PHEV). Rechargeable batteries provide the source and storage of energy for electric vehicles. Ni-Cd, Lead-acid, Li-ion, and Ni-MH are commonly available rechargeable batteries. In early days, EVs used Lead-acid batteries, but now a days electric drives mostly use Lithium-ion batteries [5], [6]. They offer better power and energy density, longer service life and are ecofriendly.

AEV suffers from the availability of a single energy storage system that may lead to loss of power causing range anxiety for an EV driver. Battery alone electric vehicle suffers from lower power density, less lifetime, battery size, and life cycle costs [7]. Also frequent charging/discharging adversely affected on the battery life [8]. Hybrid energy storage systems provide not only backup but also improves the life cycle of the battery [9]–[11]. They are efficient than single battery drives.

Integrating an internal combustine engine and an electric motor is one way of tackling this problem but still demands the use of fossil fuels and makes the system bulky. An ultra-capacitor (UC) combines the power discharging characteristics of a capacitor and a battery's ability to store energy. The capability to store and disperse energy almost instantaneously make them a good choice in HESS along with battery. The transient response is fast so that they withstand fast charging and discharging operations. They suffer from a low voltage per cell but installation and interface in a circuit is easy [12]–[16]. The combination of battery and ultra-capacitor is capable of meeting the peak load demands. HESS can affect the cost and efficiency of an EV and UC plays a crucial part in this process. On the cost-forecast assumptions of an EV, the UC pack can replace by four batteries to get the same range of operation with only increase of 1/14 th the cost. Another advantage of UC is its suitability to act as a power buffer and accommodating the energy fed back during regeneration. Super capacitors find application not only in hybrid energy systems but also for power storage [17] in applications like powering wireless sensor networks.

The choice of motor for the drive affects the EV performance. Permanent magnet motors like permanent magnet synchronous motor (PMSM) and brushless DC motor (BLDC) provides efficient drives for EVS. The latter has simple control strategy compared with the former [18]–[20]. BLDC motors have good torque and high efficiency also. They are popular in automotive, industrial, household, and robotic applications and suitable for regeneration also. A brief survey of EV, HEV, and their converter technologies are available in [21]. The power conversion technique is also important in the performance of HESS. To facilitate the current flow in both the directions, a bidirectional converter (BDC) [22], [23] becomes an essential component of the electric drive/charge systems. In this paper BLDC motor is supplied from a HESS through a bidirectional three port converter. The converter design can change with the application as in solar powered EVs [24]. The bidirectional converter manages the power flow between the load and the source. The choice of converters depends on the type of source, frequency of operation, and power demands. The power loss analysis [25] on a DC-DC buck converter is useful for converters used in EVs.

HESS with UC is capable for reducing the stress on converters. The power flow management in HESS can influence the achievement of the system when considering its range, reliability, and power dispatch. Hence, we need a controller for splitting and directing the power. Programmable controllers and heuristic controllers are present. There are different factors like the drivetrain, the drive cycle and available state of charge (SoC) that affect the choice of controllers. The power flow management in HESS demands a strong and reliable algorithm. The system complexity increases with sources and storage elements. Numerous power control strategies are available in the literature [26]–[28] for hybrid energy structures. Controllers also rely on the internet of things [29], [30] for the data flow in PV based systems or AI as in [31] for multi agent systems utilising not only solar and wind but also SC, battery and generator, and utilising piezo electric energy harvesting [32]. HESS control strategies can also address the power quality issues [33] in the system. Predictive controllers take into account the above factors and have better computation time and dynamic response [34], [35]. In general, rule-based and optimization-based controllers [36] are available. The former is easy to implement. The latter is highly drive cycle dependent and needs past/future driving information but arrive at global optimal solutions [37]. They utilize different techniques like genetic algorithm, particle swam optimization and linear/dynamic programming.

This paper proposes a regulatory control for an HESS comprising of battery and ultra-capacitor. This controller has two components; a conventional PI controller and an The fuzzy logic controller (FLC). The EMS performs two functions; regulate the SOC of UC and smoothening of battery power level. The controller with artificial intelligence technique provides faster and efficient control action. The proposed supervisory controller aims to split the power demand on the storage elements, the battery, and the UC effectively.

2. HESS WITH REGULATORY CONTROLLER

Regulatory control refers to the action of the controller whose the input conditions determine the output parameters. In this case, the controller has to allocate and distribute the available power effectively between the points of supply and the output by appraising the demand and drive. Figure 1 represents the block schematic depiction of the regulatory control scheme. The overall system has a HESS with battery/UC, a BDC for power transfer, an inverter for driving the BLDC, the controller and motor with flywheel. The controller consists of an FLC and a typical proportional integral (PI) controller. The three-phase inverter feeds the BLDC drive accordingly. The controller acquires the information regarding the angular position and velocity of the motor. The flywheel is capable of storing the energy of angular momentum and helps in extending the period of regeneration. Controller also has the data regarding the SoC of both the battery and the ultra-capacitor from the HESS. The controller operates the bidirectional converter in boost mode when the motor is running. The BDC operates as buck converter in the reverse direction during regeneration. The PI controller regulates the current flow through the battery for the charging and the discharging. Ultra-capacitor comes into play during power surges. Whenever the EV is accelerating, motor needs more input power. The ultra-capacitor supports this additional burden. Similarly, during regeneration, the energy flowing back recharges the UC first. As the duration of regeneration is very small in comparison to the forward drive, it is essential that the storage element respond fast enough.

Figure 2 shows the circuitry for battery/UC energy management system. The power electronic switch T2 is turned on to allow charge transfer from the ultra-capacitor to the load in boosted mode operation of the BDC. With S2 on inductor stores the energy from the ultra-capacitor. The inductor delivers this energy to the load through diode D1 when S2 is turned off, as UC-voltage is more in comparison with the load voltage. Regeneration happens when the load side voltage is greater than the input side voltage often caused by a downward gradient or braking. The ultra-capacitor can store this energy by the buck mode of the BDC. With T1 turned on, the inductor stores the energy. With T1 off, the stored charge flows to the battery through D1.

Figure 3 shows the schematic representation of modes of operation, namely the discharging mode, the regenerative mode and the charging/discharging mode. With S1, S2, and T0 on, both battery and UC can feed the motor. In the second mode, Q0 allows the regenerative energy to flow back to the UC and the battery. Q1 ensures charge control towards battery during regeneration. The selection of the device for charging depends on their voltage levels. If the UC power level exceeds that of the battery, the former recharges the latter.

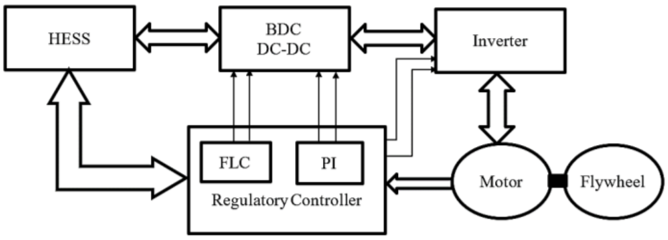


Figure 1. Block diagram representation of regulatory scheme for the HESS

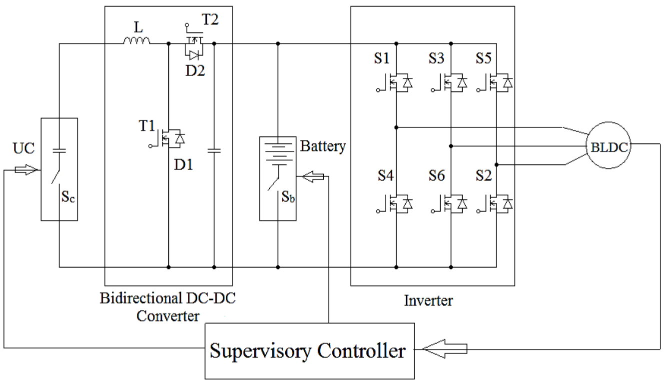


Figure 2. Circuit components for the energy management system

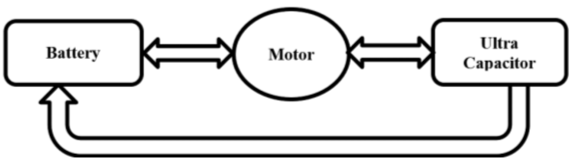


Figure 3. Modes of operation

2.1. Regulatory control strategy

During driving, an EV may face different load conditions and varying charge levels in the energy storage system. When the input variables vary over a range of conditions, heuristic approaches in the design of the controllers offers accurate solutions. Fuzzy logic controllers are easy to develop and spans over a large set of operating conditions. An FLC accomplishes the regulatory action, necessary for directing the charge flow between different components of the BLDC drive using HESS. Figure 4 shows the fuzzy logic based regulatory control strategy adapted from [7]. The energy management system (EMS) compares the output voltage (V0) with the reference value (V_0^*) for choosing the mode of operation. The EMS check the value of output power (P0) and battery output power (Pbatt) for the control action. Table 1 shows modes of operation of HESS with BLDC drive.

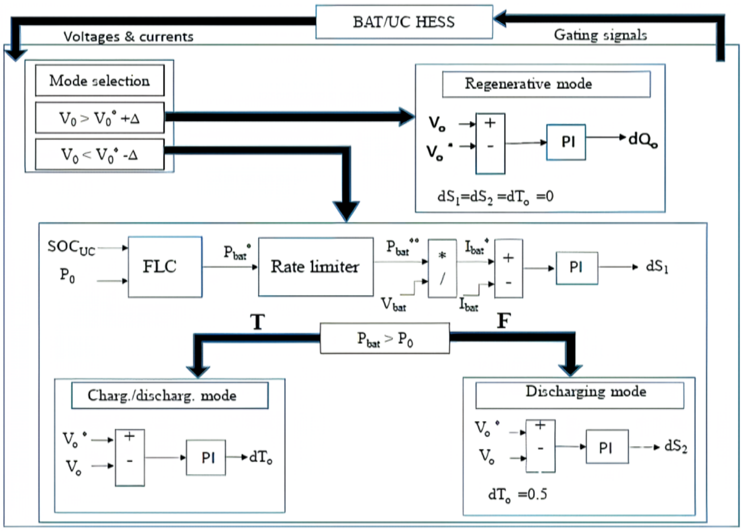


Figure 4. Fuzzy logic controller

There are three modes of operation depending on the power flow between devices. Let ΔV be an incremental value in voltage defined for determining the state of the EMS. During motoring, the reference voltage V_0^* exceeds the output voltage (V_0) indicating a positive current towards the motor. Here the either battery supplies the current for the motor alone (discharging mode of operation), or for the motor and the ultra-capacitor (charging/discharging mode of operation). During motoring, the EMS compares the available battery power (P_{batt}) and the output power (P_0) to select discharge mode or charge/discharge mode. The fuzzy logic controller (FLC) generates the gating signals for switch S1 during the motoring operation. When the motor voltage is greater than the reference value, the motor is generating. In order to retrieve the excess energy, the EMS activates the regenerating mode. A PI controller generates the gating signal for the switch Q_0 while the switches S_1, S_2, and T_0 are turned off. The bidirectional converter feeds this energy back to the storage elements.

As mentioned earlier, the conditions and variables have a wide range of variation for arriving at a decision. For example, the SoC in the super capacitor can be low, medium or high. Its value along with the required output power (P_0) determines the energy transfer from the battery (P_{batt}). The power required for driving the vehicle can also vary between at least four states. The FLC has two variables as input; the output power (P_0) and the SoC of the ultra-capacitor (SoC_{UC}). The control block gives the reference battery power (P_{batt}^*) as its output. The membership functions for the output power (P_0) have four values, which varies from very low (VL) to high (H). SOC_{UC} has three input membership functions; low (L), medium (M) and high (H). The output variable P_{batt}^* has six input membership functions namely, very very low (VVL), very low (VL), low (L), medium (M), high (H), and very high (VH). The Figure 5 shows the decision surface for the fuzzy rules stated above.

Table 1. Modes of operation

Status of V_0	Status of P_{batt}	Mode of operation
$V_0 < V_0^* - \Delta V$	$P_{batt} < P_0$	Discharging mode
$V_0 < V_0^* - \Delta V$	$P_{batt} > P_0$	Charging/ Discharging mode
$V_0 < V_0^* + \Delta V$	NA	Regenerative mode

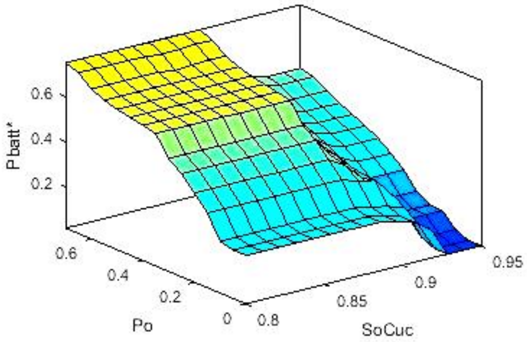


Figure 5. Fuzzy decision surface

3. RESULTS AND DISCUSSION

Simulation software is effective in checking the validity of algorithms and strategies for control problems in various aspects of engineering studies. In this study, MATLAB provides the simulation platform. A programmable device is required for implementing the controller in real time. Field programmable gate array (FPGA) is used in implementing the strategy in hardware.

3.1. Simulation results

The Simulink model of the HESS driving a BLDC motor driven from battery is shown in Figure 6. This study is based on the simulation of the hybrid energy storage system with a battery and super capacitor for the BLDC motor drive in MATLAB/Simulink. The HESS has a battery (Li ion) as the immediate source and an ultra-capacitor as the supplementary source. The model consists of the HESS, regulatory controller with FLC and PI controller, the BDC, the inverter and the BLDC motor. The BLDC motor parameters are; voltage 48 V, speed 3000 rpm, power 200 Watts, inductance L=0.375 mH, resistance R=0.5, back emf constant Kb=0.0484 V/rad/s, torque constant Kt=0.0484 Nm/A. The battery and ultra-capacitor rating are 12 V, 1.3 Ah and 24 V, 11.11 F respectively. The simulation studies shows the validity of the proposed strategy. The battery power is effectively split between the motor and the other source, namely the ultra-capacitor during the drive and fed back to sources when regenerating.

Figure 7 shows the characteristics of battery and UC during motor control. The voltage, current, SOC and power level of battery (Figure 7(a)) during the power split strategy are shown. The plot of voltage, current, SOC and power level in the UC (Figure 7(b)) have greater slope than that of the battery. It is evident that UC can respond to power surges effectively.

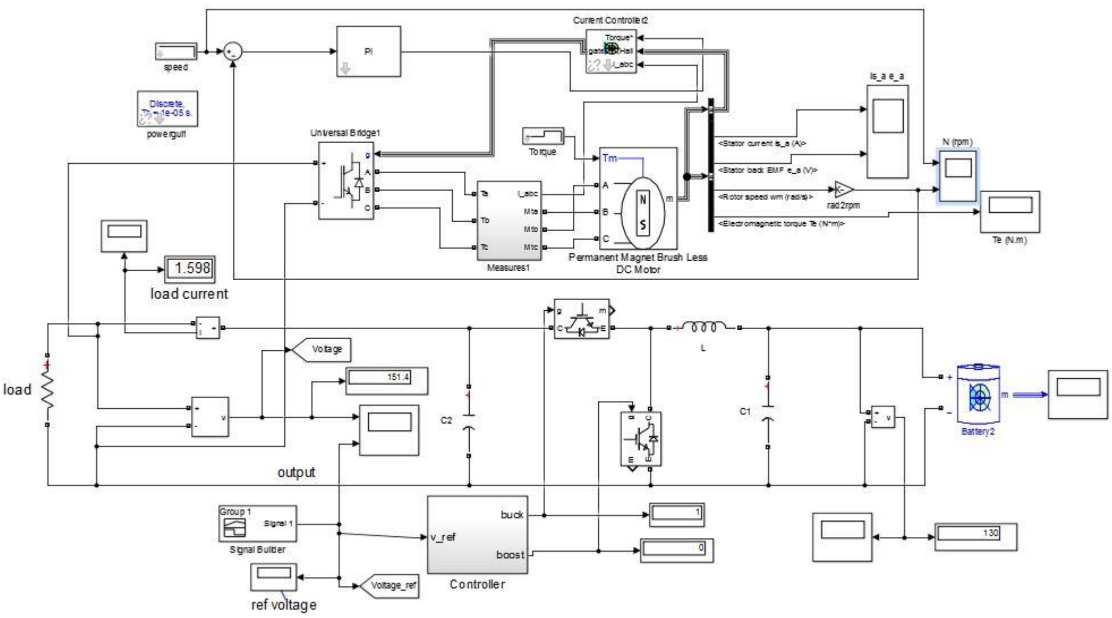


Figure 6. Simulink model of HESS with battery

(a)

(b)

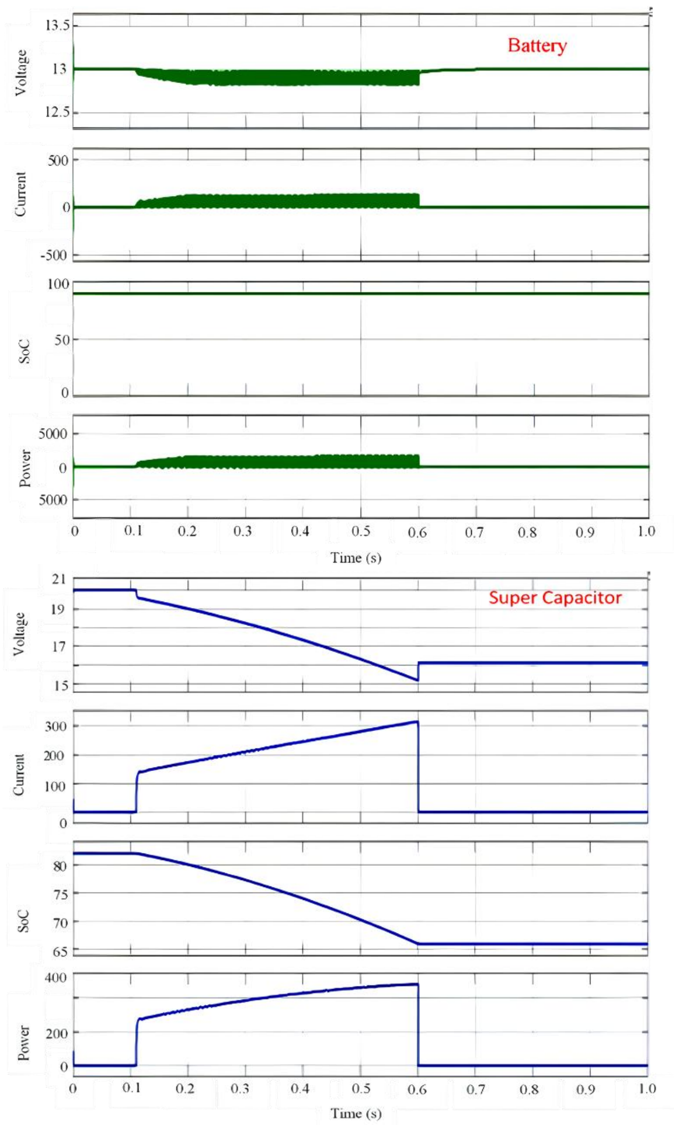


Figure 7. Voltage, current, state of charge, and power level of (a) battery and (b) ultra-capacitor

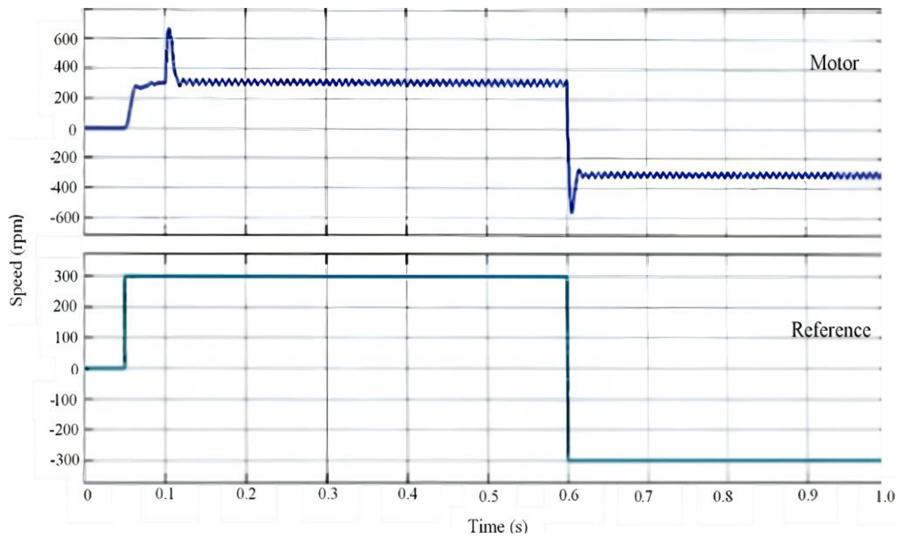
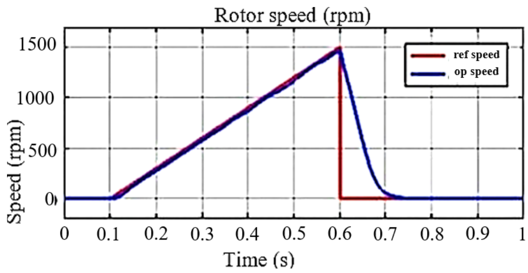
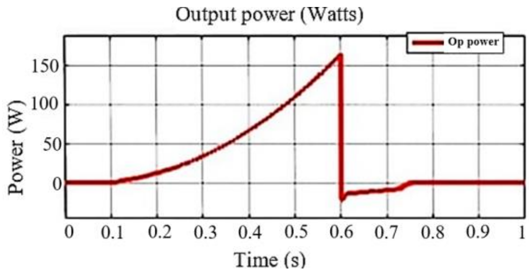


Figure 8. Motor speed curve and the reference speed curve

Figure 8 shows the speed characteristics of the BLDC motor. The actual speed follows the reference speed and reaches the value at 0.12 seconds. Figure 9 show speed (Figure 9(a)) and power 9 Figure 9(b)) during regeneration when power is fed back. The power flow reverses in regenerative mode from the forward motoring mode. The power characteristics of battery, super capacitor and the load are available in Figure 10. It was observed that during regeneration 1/3 rd of output power is developed. This value in simulation is optimistic and in actual scenario the power would be actually less than this value. During the first 0-0.6 seconds, the circuit operates in in motoring mode and goes to regeneration in the 0.6 – 1 seconds in the graph.



(a)



(b)

Figure 9. Speed and power during regeneration (a) speed of the motor and (b) power output

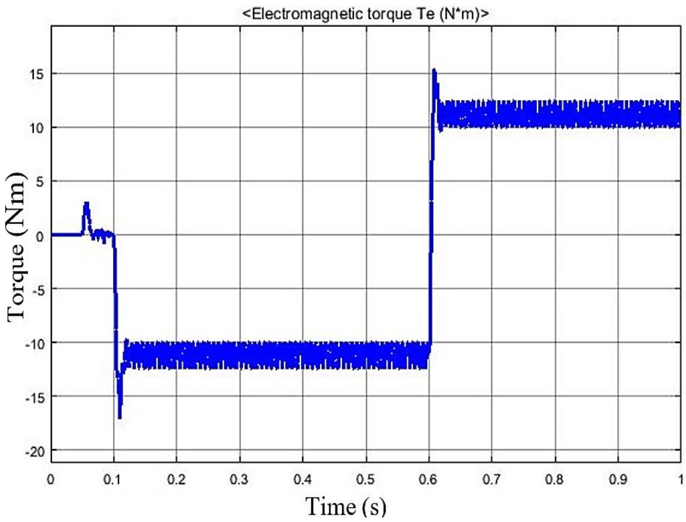


Figure 10. Torque response

3.2. Hardware implementation

The simulation model demonstrates that the proposed control strategy is able to allocate the share of power between components of the HESS effectively for different driving conditions. The experimental system consists of a HESS of battery and ultra-capacitor, BDC, inverter, BLDC with flywheel, and the HESS controller. The controller is built with FPGA Zynq^{TM}-7000 from Xilinx. FPGA is a programmable device with configurable logic blocks (CLB) connected in matrix structure. Flashing the codes written in Verilog or VHDL is easy as in PROM or using MATLAB. Table 2 presents the major components of the hybrid energy system which act as sources of energy namely battery, super capacitor, and the motor.

Table 2. Components and ratings

Component	Specification
Battery	Voltage = 12 V, Capacity= 1.3 Ah
Ultra capacitor	Voltage = 2.7 V for one UC Capacitance = 100 F for one UC, 9 UCs in series, Effective voltage = 24.3 V, Effective Capacitance = 11.11 F
Motor	Voltage = 48V Power = 200 Watts Speed = 3000 rpm= 314 rps

3.2.1. Design of flywheel

The power available for regeneration depends on the energy storage capacity. When an electric motor is driving a load like an EV, the inertia of the system does not allow the energy to dissipate easily as in regenerative braking. In the laboratory prototype of the HESS supported BLDC, a flywheel is necessary to harvest the regenerative power. This is essential as the motor has a low rating. Motor power, $= T\omega$; T is the torque and ω the angular velocity.

$$T = 200/314 = 0.63 \text{ Nm}$$
$$\text{Also}, T = \frac{J d\omega}{dt} + b\omega$$
$$\text{Let}, t = 5 \text{ s}$$
$$J = 0.01 \text{ kg m}^2$$
$$\text{Assume Speed} = 1000 \text{ rpm} = 104.6 \text{ rps}$$
$$J = 0.5 \text{ MR}^2$$
$$J_{flywheel} <= J_{motor}$$
$$\frac{1}{2}\text{MR2} <= 0.01 \text{ kg m2}$$
$$\text{Assume}, M = 800 \text{ g}, R = 0.15 \text{ m}$$
$$\text{Mass}, M = \rho V$$
$$\text{Volume}, V = \pi R^2 t$$
$$M = \rho\pi R^2 t$$
$$\rho = \text{density of acrylic sheet} = 1.18 \text{ g/cm}^3$$
$$t = M/\rho\pi R^2 = 0.009 \text{ m} = 9 \text{ mm}$$
$$M = \rho\pi R^2 t = 0.800 \text{ Kg}$$
$$\text{Jflywheel} = 1/2 \text{ MR}^2 = 0.0084 \text{ kg m}^2$$
$$\text{Energy stored on the flywheel} = 1/2 \text{ J } \omega^2 = 0.5 * 0.0084 * (104.6)^2 = 45.95 \text{ J}$$

Table 3 presents the values of battery power, SoC of UC and output power required for the fuzzy logic controller. The minimum battery power for driving the motor is 65 watts. There are six membership functions, very low (65-130 W), very low (130-195 W), low (195-260 W), medium (260-325 W), high (325-390 W), and highest (>390 W).

The ultra-capacitor charges selected are 0-40 V for low, 40-80 V for medium and > 80 for high. The other parameter output power has 4 membership functions namely very low (0-60 W), low (60-120 W), medium (120-180 W), and high (>180 W). The Zed board, based on the Xilinx Zynq™7000 all programmable SoC (AP SoC) is a field programmable gate array device useful for development of control systems and its evaluation. The controller for HESS is implemented using the FPGA controller, Zynq 7000 and coding is done using Xilinx and ADEPT software. Figure 11 shows the hardware structure. The main components are ultra-capacitor pack, battery, Zed board for realizing the controller, BLDC-flywheel assembly, the BDC, the three-phase inverter, and the driver circuit.

Table 3. FLC parameters

Value	P_{batt}	SOC_{UC}	P_{out}
Very very low	65 to 130	-	-
Very low	130 to 195	-	0 to 60
Low	195 to 260	0 to 40	60 to 120
Medium	260 to 325	40 to 80	120 to 180
High	325 to 390	> 80	> 180
Very high	> 390	-	-

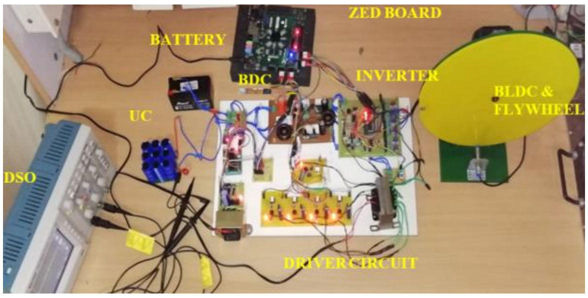


Figure 11. Hardware for evaluation

Figure 12 shows the three phase currents flowing to the stator of BLDC motor through the inverter during experimental evaluation. The input to the bidirectional converter is shown in Figure 13(a) and its output is available in Figure 13(b). An input of 12.4 V gave 26.1 V at the output of the BDC. Figure 14 shows the current waveforms during the BLDC operation. The battery current for motoring mode (Figure 14(a)) is in forward direction while it has reverse polarity in the regenerative mode (Figure 14(b)).

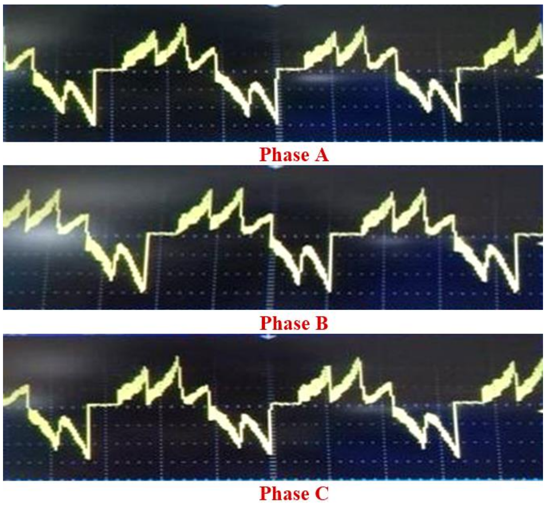
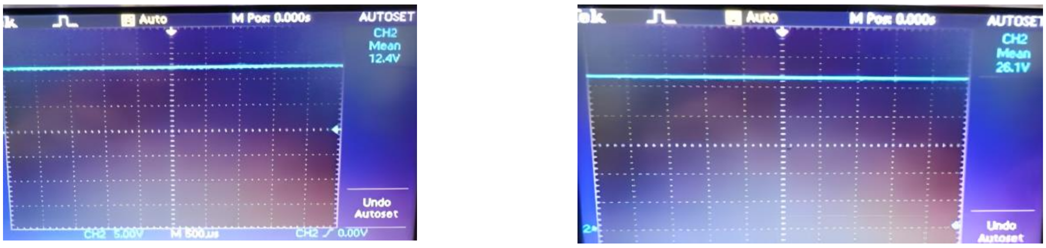
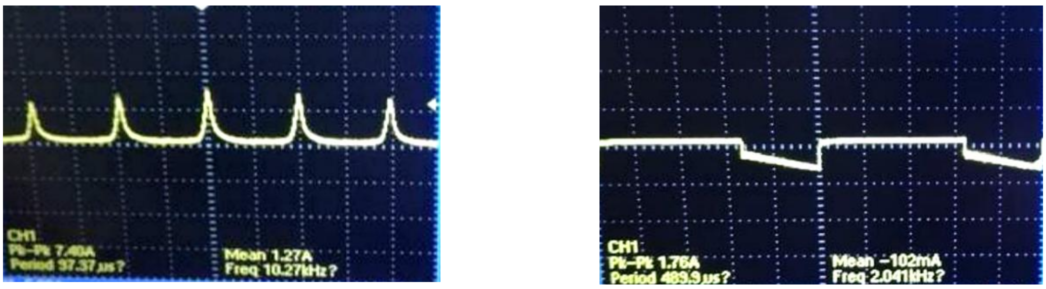


Figure 12. Stator phase currents



(a) (b)

Figure 13. BDC (a) input and (b) output



(a) (b)

Figure 14. Battery current (a) motoring and (b) regeneration

4. CONCLUSION

In this paper, we discuss the composition, operation, and implementation of a new regulatory controller for battery/UC based HESS. This system is suited for numerous applications like electric vehicles. The transient power characteristics of UC provides better regulation and regeneration for electric vehicles in comparison with EV with only battery source. The bidirectional power flow from the HESS towards the motor and vice versa needs a power converter. A three-port BDC allows boost operation in the forward motoring action and buck operation in the reverse regenerating mode. Multi-port bidirectional converters can effectively combine different sources to enhance the storage capacity of energy management systems. The regulatory controller has a PI Controller for regulating the battery charging/discharging and an FLC for splitting and controlling the energy transfer between UC, battery and the motor. FLC has the advantage of accommodating a wide range of operating conditions in comparison with conventional controllers and emulate human-like thinking to action. Simulations in MATLAB toolboxes shows the efficacy of the scheme discussed in the paper. The results from simulation studies validate the effectiveness of the regulatory controller, which is able to split the power between the elements as per demand. The controller is implemented using FPGA. The design and addition of a flywheel is necessary to harvest the available power during regeneration. For an EV, regeneration not only charges battery, but also allows electrical braking leading to less wear and tear for the mechanical parts of the vehicle. Experimental results with a prototype confirms the validity of the simulation studies.

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