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Energy Efficient Hybrid Electric Vehicle Driven by Brushless DC Motor

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Abstract: Electric Vehicle (EV) brings zero emission concepts as positive result of electric motor propulsion system. Zero emission concepts can not only be applicable to a built in EV but also in converting a fossil fuelled vehicle into its electric version. Brush Less DC motor (BLDC) have been demanding as in-wheel motor in EV because of its high efficiency, desired torque versus speed characteristics, high power density and low maintenance cost. The major disadvantages voiced by the existing system are the charging woes, travelling range, overloaded batteries, lack of power, pollution. To tackle theses disadvantages so as to improve the driving range of EV along with efficient usage of energy a creative supervisory energy management strategy for Hybrid Energy Storage System (HESS) comprising of battery and super capacitor is proposed. Moreover a new Regenerative Braking System (RBS) is incorporated for a two-wheel EV with HESS driven by BLDC motor. The BLDC motor control is utilized with the traditional Proportional-Integral-Derivative (PID) controller while the distribution of braking force is determined with the fuzzy logic control. In this paper the battery state of charge, super capacitor state of charge, braking force and dc bus current are analyzed. Simulation results prove the effectiveness of proposed system and all the results are validated.

Keywords: Brush Less DC (BLDC) motor; Electric Vehicle (EV); Hybrid Energy Storage System (HESS); Regenerative Braking System (RBS)

I. INTRODUCTION

The policy to use alternative energy source other than oil has been a big subject in developed countries as a mission to lessen oil dependency and as an effort to reduce the cost of energy. India unveiled National Electric Mobility Mission Plan (NEMMP) 2020 in 2013 to address the issues of National energy security, vehicular pollution and growth of domestic manufacturing capabilities. But the key challenges to adoption of EV in India are primarily due to low penetration of charging infrastructure and perceived higher initial cost of acquisition. Thus the policies open new markets for electric vehicles. In-wheel motor technology is being used in modern EVs to improve efficiency, safety and controllability of vehicle. BLDC motors have been demanding as in-wheel motor in EV because of high efficiency, desired torque versus speed characteristics, high power density and low maintenance cost. Complementary features of batteries and Super Capacitors (SC) can be effectively used in Hybrid Energy Storage System. The utilization of the HESS in EVs offers many advantages such as efficient regenerative braking, battery safety and improved vehicle acceleration. It is estimated that in conventional braking more than 80% of energy is being converted to heat through friction. Regenerative Braking System (RBS) plays an important role in capturing more than half of this wasted energy and put it back to work. Implementing the concept of RB in EV’s is a small, yet a very important step to prolong the life span of battery system, without the need to be plugged into an external charger. It is to be noted that the EV cannot operate all times with Regenerative Braking System (RBS) thus, a Mechanical Braking System (MBS) is also necessary for the safe operation of EV with the safe transition from RBS to MBS at times necessary. In this paper a new regenerative braking system based on Fuzzy Logic Controllers is proposed for EVs with HESS and driven by BLDC motor.

II. BLDC MOTOR AND CONTROL

Brushless DC Motor (BLDC)/electronically commutated motor/ synchronous DC motor are synchronous motor [1]. Their constructional structure is similar to that of a Permanent Magnet Synchronous Motor (PMSM). BLDC motor have rotor on which permanent magnets are mounted and stator on which with the armature windings are fixed with a laminated steel core as shown in Fig.1.BLDC motor are powered with a DC source via an inverter that produces an AC

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current which drives the each phases of motor. BLDC Motor have two kinds of back-emf signals sinusoidal/trapezoidal. In this paper a trapezoidal back-emf signaled motor is used.

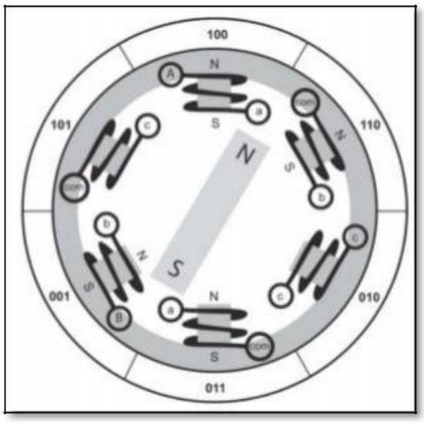

Fig.1.BLDC Motor Star Connected

Hall Effect sensors are used in BLDC motor to detect the position of permanent magnet and the signals from sensors are used to adjust the PWM sequence of 3 phase bridge inverter. Fig.1 shows the digital code shown round the peripheral of motor gives the rotor position. The six outputs of the rotor position controls the upper and lower phase switching of MOSFET. The relationship between the each sectors and the switching states depicted by the drive circuit firing in fig 2. The main control of the electronic inverter is BLDC motor control and the commutation is achieved by controlling the order of conduction on the inverter bridge arm [3].In order to control a BLDC motor, it is essential to know the position of the rotor which determines the commutation which is done with the help of hall sensors [2]. Hall Effect signals of motor are produced according to electrical degree. Table 1 shows Hall Effect signal values according to electrical degree of rotor. A typical arrangement for driving a BLDC motor with hall sensor is shown in figure 3. The major part of the circuit consists of three phase inverter comprising six IGBTs to which three coils of BLDC motor are connected, Hall sensors and drive controller. Three Hall Effect sensors (Hall A, Hall B, Hall C) are used to indicate the rotor position. The feedback from hall sensors are fed to a drive controller [3]. The output from the drive controller consists of pulse width modulated (PWM) signals which is fed to the H Bridge inverter. The average voltage and average current to the coils are determined by the pulse width modulated signals. Hence the motor speed and torque are controlled.

Table I- Hall Effect Sensors

Electrical Degree	Hall1	Hall2	Hall 3
0-60	1	0	1
60-120	0	0	1
120-180	0	1	1
180-240	1	1	0
240-300	1	1	0
300-360	1	0	0

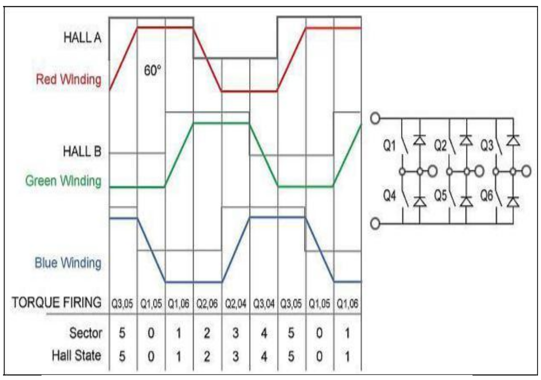

Fig.2 Back EMF BLDC motor phase

In order to generate magnetic flux two pairs of permanent magnets are used by the rotor itself. Since the motor has two pairs of magnets, to spin the motor once, two electrical revolutions are required . A six step commutation sequence is employed by the system for each electrical revolution [1]. Thus the voltage vector of BLDC motor is divided into six, which is in correspondence with the Hall Effect sensors signal. Each motor lead is connected to high-side and low-side switches. At each step, two phases are on with one phase feeding current to motor and the other providing a current return path. The third phase will be open then.[1]. The current in the circuit of motor-battery is reversed to attain regenerative braking. Pulse Width Modulation (PWM) control is implemented for an active braking control. Figure 4 shows the relation between armature current and back EMF for phase A, B and C. The higher arm switches T1, T3, T5 are always kept off. And lower arm switches T4, T6, T2 are controlled for the power reversal during regenerative braking. When the speed of BLDC motor is low the back EMF of the stator winding is incapable to reach the voltage across battery. In this case a boost circuit can be established by the inductances in the stator of motor [2]. Through this inductor accumulator the dc bus voltage is upraised to accomplish the retrieval of brake energy. To achieve this all the switches in the higher arm of the inverter are turned off and the lower arm switches are only controlled throughout the regenerative braking mode. Thus the control, during normal motoring mode is done by operating the switches in accordance with the hall sensor signals [3]. At this time (motoring mode) both upper arm and lower arm switches are used. It is to be noted that both the switches in the single arm of the inverter cannot be operated simultaneously. During regenerative braking mode the motor operates as generator. The energy reversal between motor and battery can be done by operating only the lower arm switches. During regenerative braking (generator mode) only the lower arm switches are controlled while the upper arm switches of the inverter are kept off for all Hall signals [4].

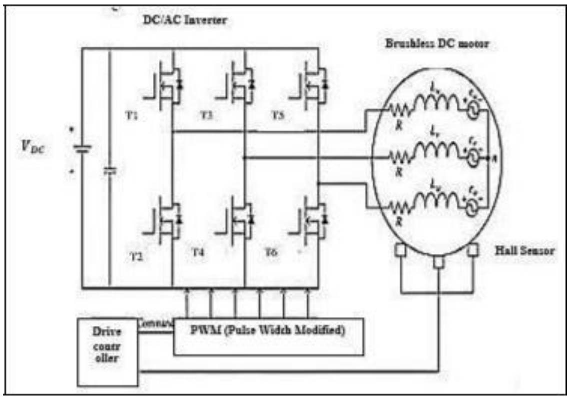

Fig.3 BLDC control by H-Bridge inverter

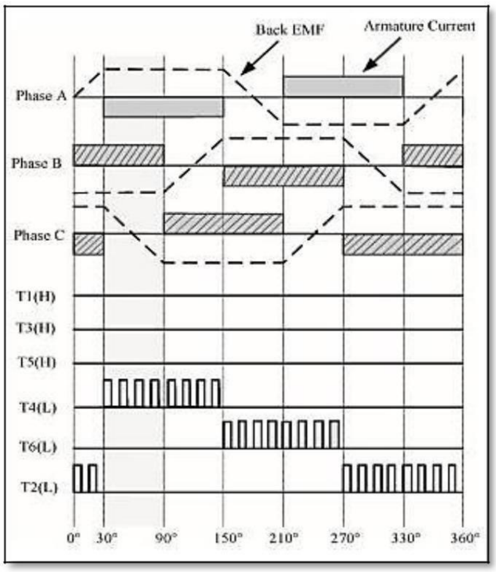

Fig.4 Regenerative braking with single switch

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III. PROPOSED SCHEME

The proposed scheme consists of a HESS pack which contains a battery pack, parallel with a SC pack as shown in Fig 5. The HESS pack is incorporated in a BLDC motor driven Electric Vehicle. The control strategy mainly compares four inputs, where two inputs (brake pedal, accelerator pedal) are feed backed from the vehicle along with the battery SoC and SC Soc from the HESS pack. The control logic thus compares all the four inputs to calculate the amount of regenerative braking demand required.

A. Driver Controller and Inverter: The driver controller plays an important role in switching the switches of the H pulse inverter circuits thereby energizing each winding of the 3 phase motor windings.TLP250 is used as the MOSFET driver for the H pulse inverter circuit. The H bridge inverter driven by MOSFET driver is used to drive the BLDC motor during different working conditions of the electric vehicle.

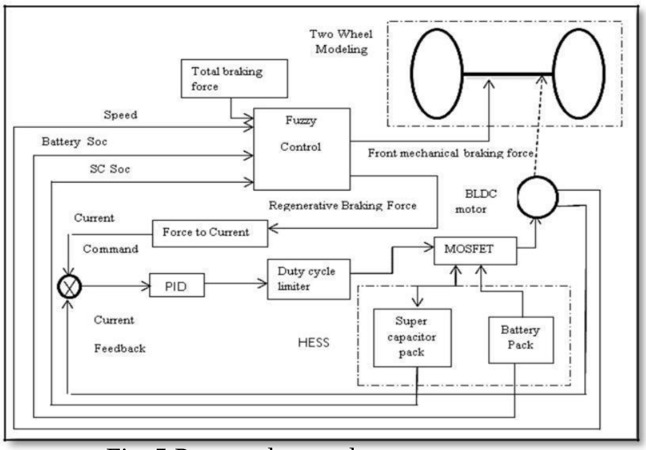

Fig. 5 Proposed control strategy system

B. Hess and regenerative braking strategy: In proposed system the HESS consist of battery and super capacitor pack. The battery and super capacitor are connected in parallel to the DC bus through bidirectional DC - DC converter, which enable separate control over the power flow for each sources. This permits dividing energy between the two sources depending upon the state of charge of each sources and vehicle dynamic displacements. The short driving distance is one of the weakness for the development of EV. RBS is an effective approach to extend the driving distance of an EV by effective recycling of braking energy. It is seen that large portion of kinetic energy of a typical vehicle is wasted by the rear and front mechanical braking. Since the BLDC machine acts as generator during regenerative braking, kinetic energy of the vehicle at this time can be stored in the HESS by the reversal of current flow. In order to achieve this function, the DC link voltage needs to be boosted and energy is transferred to the HESS. In the proposed control strategy, HESS consist of super capacitor assisted Li-Ion battery through DC-DC converter. According to this, during normal working condition battery is the main energy source and in regenerative braking condition, braking energy is stored in the super capacitor ; then the braking energy is transferred to the battery pack under non- braking condition. In order to recycle the braking energy during the braking process and prevent the battery damage, a super capacitor is added to the system. Fuzzy logic look up table are generally utilized to determine the values of the regenerative braking force and the mechanical braking force for the front wheel depending on the vehicle condition such as speed, battery State-of-Charge(SoCB), super capacitor (SoCC). When the SC SoC is less than 10%, it is unsuitable for charging. So the breaking force is low, when the SoC value is in between 10% -90%, the SC can charge with suitable current. In order to prevent the excessive charging of the SC, the current should decrease when SoC is high and the breaking force is low. From the fuzzy control structure the regenerative breaking force can calculated. Based on this regenerative breaking force can stored in the super capacitor. It is seen that the fuzzy controller controls the regenerative braking torque as the EV speed decreases, ensuring reliable operation of the braking system. Additionally, the braking force distribution between the rear wheel, front wheel and division of the mechanical and regenerative forces are fulfilled real-time by the fuzzy controller.

C. Simulation Results: The fuzzy logic control strategy is applied for the proposed system. The proposed fuzzy control logic have four inputs, that includes state of charge of battery, state of charge of super capacitor, speed of vehicle and the front breaking force. The output variable is the ratio of regenerative breaking force to front breaking force as shown in equation (1).

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Brake Force	SoCB	Speed	SoCC	Membership functions
H	H	L	C	MF0
H	M	L	D	MF1
M	H	H	C	MF2
M	L	H	D	MF3
M	M	H	D	MF4
M	H	L	C	MF5
M	M	L	D	MF6
L	H	H	C	MF7
L	L	H	D	MF8
L	M	H	D	MF9
L	L	M	D	MF10
L	M	M	C	MF11

Fuzzy logic look up table were formulated depending on the vehicle condition such as speed, battery State-of-Charge (SoCB), super capacitor (SoCC) and total brake force. Table II shows the fuzzy Logic Control Rules. Thus the Regenerative braking system of BLDC motor drive system with digital controller was implemented and simulated using MATLAB and Simulink. Membership functions of fuzzy control are as shown in fig 6.

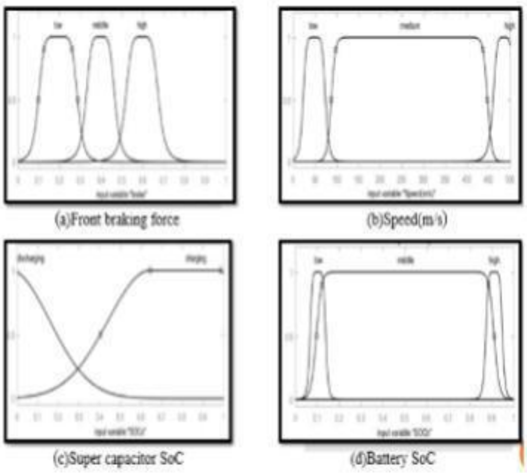

Fig. 6 Membership functions of fuzzy control.

The simulation results and test are represented as follows.

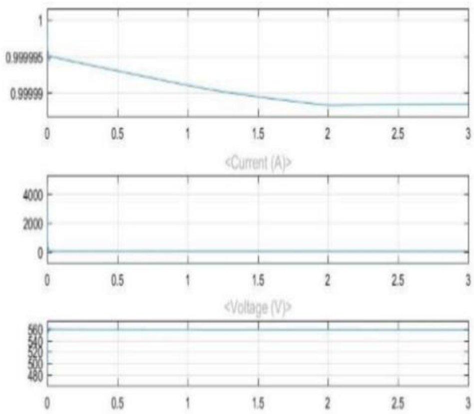

Fig.7.Charging of Battery SoC from lower arm pulses of 3 phase inverter

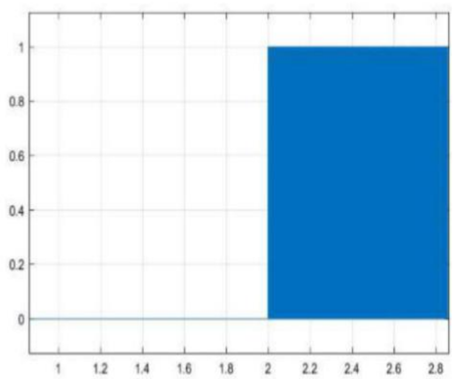
Fig.8 Regenerative braking pulses

IV. IMPLEMENTATION

The hardware consist of FPGA controller, BLDC motor, ADC(Analog to Digital Converter), toggle switches for getting the input of break and acceleration, HESS pack which include both battery and super capacitor, and PWM driver circuit. The inputs to the FPGA controller are hall sensor signals, Battery SoC and SC SoC from HESS, throttle connected via ADC and front and rear wheel force demand. The output signal are triggered for switch on and off of the MOSFET switches, hence speed control can achieved. As said above one of the input to FPGA is a throttle, which is a variable resistor that helps to propel the vehicle forward. Generally it is an analog value so an ADC is required to convert this analog value to digital. A VRLA chargeable battery of 12V*4 No. is used to give the power supply for the whole module, and a super capacitor pack is also incorporated to assist battery pack on peak demand condition. A voltage regulator circuit is used to provide 5V that is used to drive the FPGA controller. The voltage needed for the BLDC motor is directly taken from the 48V battery. The voltage regulator circuit is provided to step down 48V to 5V for driving throttle and Spartan 3E FPGA. The control mechanism for BLDC motor is typically done by means of a converter. To produce appropriate control signal to perform the desired function, a special purpose processor or a programmable logic devices is essential which can produce simpler, faster, efficient and cost effective control strategy. For the implementation of this digital controller, we choose Xilinx Spartan - 3AN FPGA processor. The digital control algorithm is written using VHDL coding and is dumbed on to the FPGA board. FPGA receives the hall sensor signal from the BLDC motor and produce appropriate gate pulse which drives the switches. The PWM signal is generated from the Spartan FPGA processor by writing VHDL program to control the inverter switches. The speed of BLDC motor is controlled by taking the throttle feedback using ADC to the FPGA controller and the speed is adjusted by adjusting the duty cycle of the PWM pulse. The speed of the motor is directly proportional to the applied voltage across the winding. Hence by varying the average voltage the speed can be controlled.

V. CONCLUSIONS

In this paper, a new RBS is proposed for a two-wheel EV with HESS driven by BLDC motor. Also a creative supervisory energy management strategy for Hybrid Energy Storage System (HESS) comprising of battery and super capacitor is proposed. The kinetic energy of the vehicle is harvested by HESS during regenerative braking using appropriate switching template of the inverter. The Fuzzy controller is utilized to control the braking force distribution to rear wheel of the EV. And the PID controller is used to control the duty cycle of the PWM in the inverter to realize constant torque braking. Total breaking force, Battery SoC, SC SoC and speed are chosen as the four important fuzzy control input variables. Appropriate brake current to produce brake torque is obtained by RBS. In the proposed system PID controller used to adjust the BLDC motor PWM duty to obtain the constant brake torque In comparison with other similar types of the EVs, the proposed system has the superiorities of being high-efficient. It can be concluded that along with improving the driving range, the implementation of HESS provides efficient energy management strategy for EV. Further improvement can be brought in by including a fuel cell pack along with the existing HESS system which ensures a more efficient control strategy.

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