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Regenerative Braking of BLDC Motor using Fuzzy Control for Electric Vehicles

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***Abstract*—This paper refers to an effective model using MATLAB Simulink for Regenerative Braking of a BLDC motor for an Electric Vehicle. In this method the inverter which is used to drive the motor, alone is used. The back EMF of the motor during regeneration will be less than the battery voltage even if the brake is applied while the vehicle is running at its highest speed. So the regenerated energy has to be boosted. This can be attained by controlling the switching of the lower switches of the inverter with the help of PWM switching. This boosted energy can be accumulated to the battery or supercapacitor or both. Here battery-supercapacitor energy storage is used. Thus by using electric braking a smooth braking is made possible also the driving range can be increased, since batteries are getting charged with the regenerated energy. The simulation is done by using MATLAB/Simulink.**

Keywords*— *Electric vehicles, regenerative braking; BLDC motor; inverter; battery; supercapacitor; Fuzzy Logic;

I. INTRODUCTION

Electric Vehicles are really becoming the need of the hour, since the atmospheric pollution caused by the conventional Internal Combustion (IC) engine vehicles is alarming. The use of Electric Vehicles (EV's) has increased afresh. Most EV's are driven by energy accumulated in a battery. To use the battery's energy productively is a prime challenge in EV's. The batteries have some shortcomings, such as limited life-cycle, limited power density as well as high cost. The Electric double layer capacitors, known as supercapacitors, are high capacitance capacitors that offer many outstanding features such as high power density, long life-cycle, and wide operating temperature range. [9] Even though the supercapacitor has many benefits, it cannot be used as the main Energy Storage System (ESS) since its energy density is relatively low [2].

Brushless dc (BLDC) motors have many merits over brushed dc motors and induction motors, such as simple structure, high efficiency, high dynamic response, higher speed range, large starting torque, noiseless operation, etc.

Thus, BLDC motors find its application in EV's [5]. The energy wasted during braking in traditional vehicles with IC engines can be harvested effectively with help of regenerative braking in EV's. Regenerative braking is the process of feeding energy from the motor drive back into the battery during the braking process, when the vehicle's inertia forces the motor into generator mode. The energy thus generated won't be sufficient to be even to the battery directly. The regenerated energy has to be boosted, if we use an additional boost converter for this the cost, size and complexity of the entire system increases. An effective solution for this is to use the motor's own power converter switches and winding inductance [1]. The charging current of regenerated power has to be controlled to prevent the battery from any possible damage. For regeneration a current developing path is provided by a proper control of inverter as a boosting operation. For higher vehicle speeds and lower State of Charge (SoC) values, the battery pack must be protected properly from harmful excessive charging currents. The use of regenerative braking in EVs can increase the driving range up to 15% with respect to EVs without the regenerative braking system (RBS) [3]. But mechanical brake also will be present in vehicle, since in all the conditions regenerative braking may not be possible, i.e; if brake is applied when battery is fully charged regenerative braking cannot be accomplished. The BLDC motor current control is done by using PI controller and braking force distribution is controlled by fuzzy logic.

II. BASIC BLOCK DIAGRAM

The basic block diagram for regenerative braking of BLDC motor with battery-supercapacitor energy storage is demonstrated in figure 1.

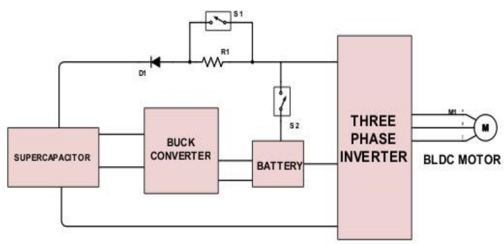

Fig 1: Block Diagram for regenerative braking of BLDC motor

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The battery pack is paralleled to the supercapacitor through diode D1 which remains reverse biased until the supercapacitor voltage is higher than the battery pack voltage. A limiting resistance is added in series with the diode D1; it helps in protection of battery. When the supercapacitor module is charged to a level of the battery voltage, the limiter resistance is bypassed using a mechanical switch.

There are two modes of operation, normal mode and regenerative braking with battery and supercapacitor. In normal mode, the battery solely supplies the motor. During braking the motor works as generator and thus regenerated energy is boosted, diode D1 gets forward biased and energy is stored in the supercapacitor. The supercapacitor used is of high voltage compared to battery, so energy stored is step down using the buck converter and then used to charge the battery.

III. Equivalent Boost Circuit

The working of the converter during regenerative braking can be described with the help of the circuit diagram demonstrated in figure 2(a). A specific switching pattern is applied alone to the lower switches S2, S4 and S6 of the inverter. The switches are then controlled via a high-frequency PWM signal. When the upper switches are turned off, the diodes transfer current to the battery side. For easily regulating the regenerative voltage, single-switch modulation mode is adopted, where the active switch in the lower side is modulated in turn. Specifically speaking, turns only one of the lower switches to be periodically PWM, and keeps the other five switches OFF. For a whole electrical cycle of the regenerative charging process, each switch is modulated within 120 electrical degrees [10].

Therefore, the vehicle's kinetic energy is converted into electrical energy, which avoids the wastage of energy, lengthens the life of batteries, and increases the driving range.

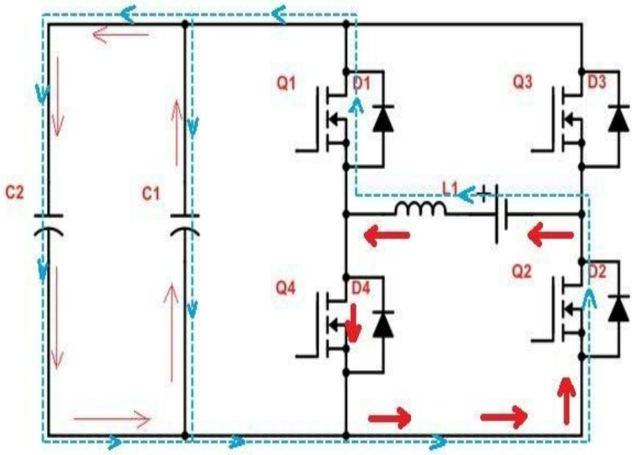
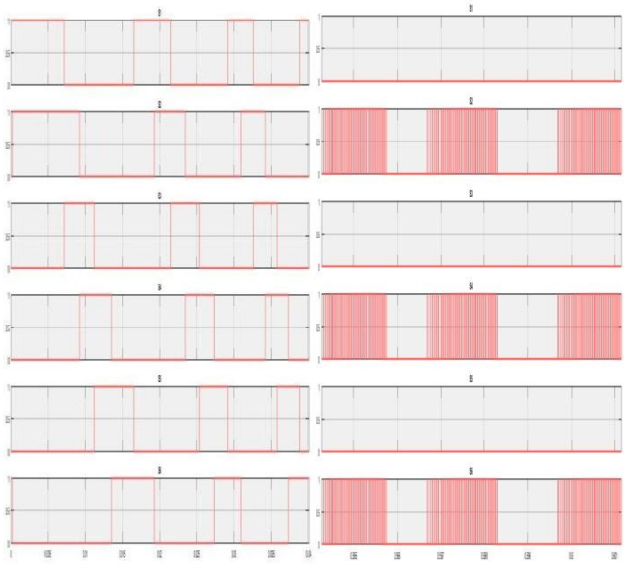


Fig 2(a): Equivalent Boost Converter

The waveform of switching pulse given for controlling the MOSFET during motoring operation is demonstrated in figure 2

(b).During braking the MOSFET is controlled with the help of PWM switching and this is evident from the waveform demonstrated in figure 2 (c). The switches in the upper legs S1, S3 and S5 are turned off and PWM switching is given to the lower switches alone.



time
(b)

time
(c)

Fig 2 :(b) Switching pulses during motoring operation; (c) Switching pulses during Braking operation

IV. Modes of Operation

A. Vehicle in Normal mode

When motor power is less than or equal to battery power the vehicle remains in normal mode of operation. During normal mode the battery solely supplies the motor.

The energy flow during normal mode of operation is demonstrated in figure 3(a). In BLDC motor electronic commutation is used to obtain the commutation sequence, with the help of hall sensors rotor position is sensed and proper commutation sequence is generated.

The diode remains reverse biased during this mode of operation since the voltage of supercapacitor is higher than battery voltage and hence there is no effect of the rest of the elements in the circuit. The supercapacitor remains idle and the buck converter is in OFF state.

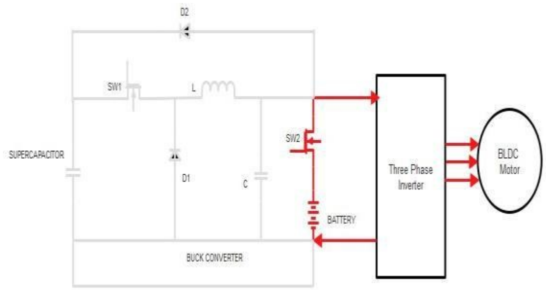


Fig 3(a): Vehicle normal operation mode

B. Vehicle in Regenerative Braking mode

In Regenerative Braking mode the dc-link voltage will be boosted with the help of appropriate switching signal pulses to the lower switches of the inverter. So the diode D2 gets forward biased due to the boosted dc link voltage and the braking energy is harvested in the supercapacitor module. Instead of using an extra DC-DC converter, here boosting is

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accomplished by using the motor's own winding inductance and bidirectional switches of the inverter. It reduces the components required and also the overall cost. The working of the equivalent boost converter which is realized from the inverter has been discussed in the Section III. The energy flow during regenerative braking mode of operation is demonstrated in figure 3(b).

This mode of operation is activated whenever a brake is applied. When brake is applied the dc link voltage gets boosted and stores the regenerated energy to the supercapacitor, simultaneously the buck circuit is also turned ON. The Supercapacitor used is of high voltage, when compared to the battery voltage. The buck circuit is used to step down supercapacitor voltage to the battery voltage and charge the battery. Here the supercapacitor and battery are getting charged simultaneously, so whenever charge has to be stored to the supercapacitor it can be done. The energy is not directly stored to the battery on the grounds that if battery undergoes fast charging and discharging cycles frequently it affects the battery life. Fuzzy Logic Control (FLC) is used for proper braking force distribution and even braking, it is discussed in detail in Section V.

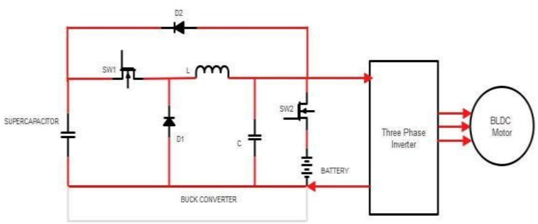


Fig 3(b): Vehicle in Regenerative Braking mode

V. Fuzzy Logic Controller

In Fuzzy Logic Controller (FLC) the inputs and outputs can be defined with the help of custom or available membership functions. Mamdani type FLC available in MATLAB Simulink is used here and the model is demonstrated in figure 4(a). Fuzzy rules can be written according to the requirement. Here FLC is used for the braking force distribution between the front and rear wheels for a smooth and efficient braking. The braking force distribution depends on the braking force, SoC of supercapacitor, Speed of the motor etc. [4]

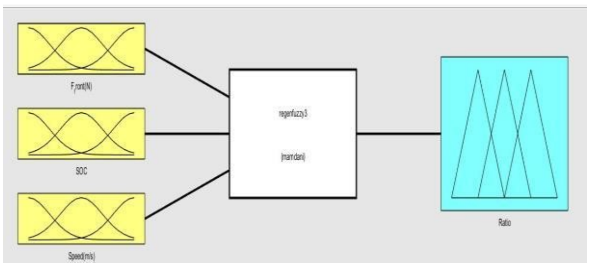


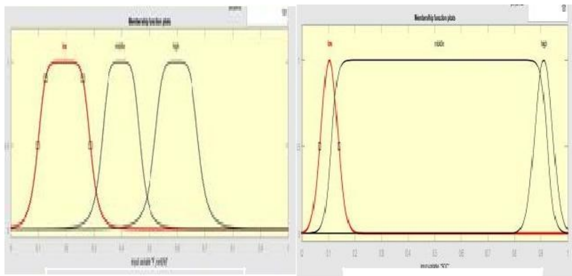
Fig 4(a): Fuzzy Logic Controller (Mamdani)

The brake requirements of a driver and safe driving are interconnected. The braking force values can represent the braking distance and required time by the driver [7]. Large braking force means the vehicle has to be stopped immediately. During such situations the proportion of regenerative braking force has to be reduced. When braking force is middle the ratio of regenerative braking force can be increased. Also for small braking force a large regenerative braking force can be applied so that maximum possible energy can be recycled.

When SoC is less than 10%, the internal resistance of the battery will be a high value and during this time it's not desirable to charge the battery; so regenerative braking force has to be small. When SoC is between 10% and 90% the battery can be charged, so regenerative braking force can be increased correspondingly. But when SoC is beyond 90% charging current has to be decreased to avert lithium ion deposit so regenerative braking force has to be decreased.

Vehicle speed is an important factor in braking safety. When speed is low regenerative braking force also should be low and for medium speed it can be increased to a proper value. For high speed, the regenerative braking force is set at the highest, so that maximum energy can be harvested.[8]

As discussed in the earlier section there are three input variables, which are braking force, SoC and speed of the motor. The figure 4(b) shows the membership function for braking force where the concourse selected is {low, medium, high}.



(b) (c)

Fig 4(b): Membership function for braking force; 4(c) Membership function for SoC

The membership function for SoC is demonstrated in figure 4(c), the concourse is chosen as {low, medium, high}.The membership function for speed is chosen as {low, high} also the universe of discourse selected is [0, 2500].The membership function for speed is demonstrated in figure 4(d).

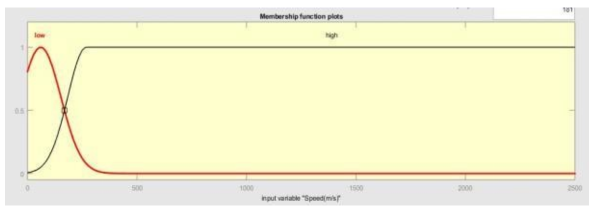


Fig 4 (d): Membership function for Speed

The membership function for output variable is demonstrated in figure 4(e).

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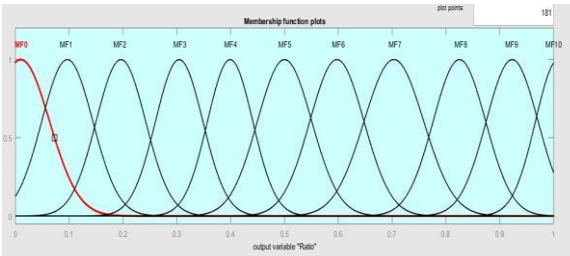

Fig 4(e) : Membership function for output variable

The fuzzy rules are the core of any FLC; the control model uses the form of three inputs and one output structure (MISO). The rule is in the form IF premise1, premise2, and premise3, THEN conclusions. [6]

VI. Simulation Results

The MATLAB Simulink model for regenerative braking of BLDC motor is demonstrated in figure 5(a). Here a BLDC motor is driven by using an inverter by sensing rotor position from the hall sensors and these signals are converted to pulses by using appropriate logic. Initially the gate pulses are given from the hall sensor signals, after a certain simulation time brake is applied.

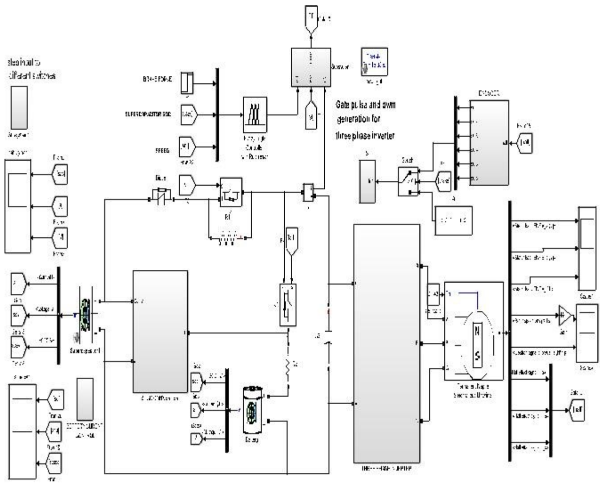

Fig 5(a): Simulation Diagram for regenerative braking of a BLDC motor

After applying brake the upper leg switches continues to provide pulse from the hall sensor and the switching of bottom leg switches are controlled by PWM switching. This PWM switching provides a path towards the source for the regenerated voltage, also by giving this switching an equivalent boost circuit is formed in the inverter and the winding of the motor acts as the boosting inductor. The battery current is controlled by the help of a PI controller. The reference to the PI controller is given as the output of FLC. The PI controller output is compared with a repeating sequence to get PWM switching pulse thus controlling the battery current, making the output of AND logical operator 1, so now the input to the OR operator becomes 1,0. It means that the gate pulse to the bottom leg switches is now given with help of PWM switching and gate pulses generated from the hall sensor signals is cut off thereby making boosting possible.

After the brake is applied the regenerated energy is boosted this is stored in the supercapacitor and simultaneously the battery is charged with the help of buck converter. These are validated in virtue of the simulation results. The waveform for motor speed is demonstrated in figure 5(b). An initial speed is set in the motor parameters so that the simulation time required to reach the rated speed can be reduced.

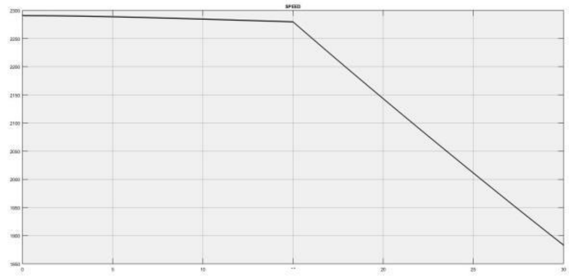

Fig 5(b): Motor Speed

The battery current, voltage and SoC are demonstrated in figure 5(c) respectively. From the waveform of battery parameters it can be seen that in normal mode of operation the battery SoC, current and voltage reduces and during regenerative braking mode the battery voltage increases along with a slight increase in SoC, there is negative current which denotes the charging current of battery.

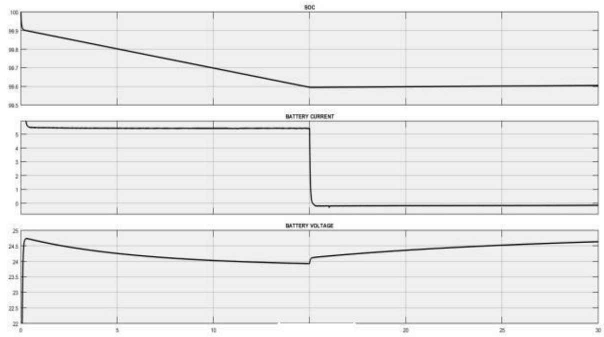

Fig 5(c): Battery parameters

The supercapacitor parameters are demonstrated in figure 5(d). The supercapacitor voltage, current and SoC waveforms it can be inferred that till brake is applied, i.e; up to 15s simulation time the supercapacitor current is zero whereas the voltage and SoC remains constant. During regenerative braking mode the voltage and SoC increases and also current is negative which indicates the charging of supercapacitor.

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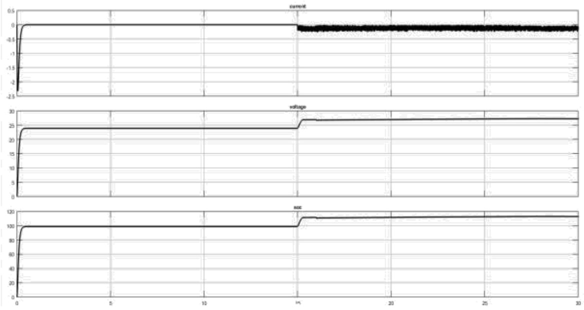
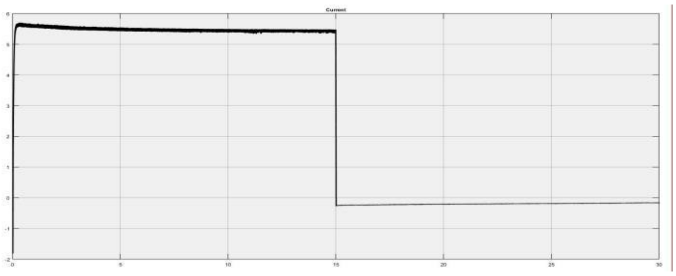


time

Fig 5(d): Supercapacitor parameters

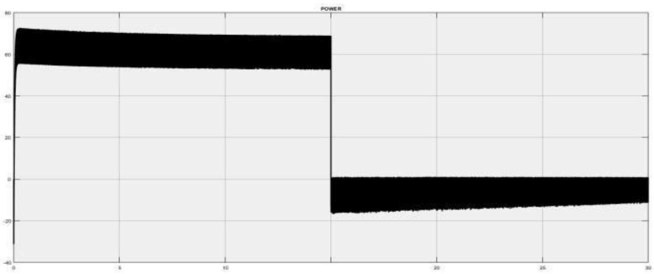
The current flow in the circuit towards the load during normal mode of operation and the current flow towards the battery-supercapacitor energy storage after regeneration is demonstrated in figure 5(e).



time

Fig 5(e): Controlled towards supercapacitor

The regenerative braking using BLDC motor with supercapacitor-battery energy storage is simulated in MATLAB Simulink as a prototype of the same, so that it can be realized experimentally as a future work. The power of the motor used here is 60W and from waveform demonstrated in figure 5(f) it can be observed that nearly one-third of power is obtained back during regeneration



time

Fig 5(f): Motor Power

The rating and specification used here are mentioned in the Table I.

Table I: Specifications

Components	Specification
Motor, Power	60W
Voltage	48V
Torque	0.12 Nm
Inertia	0.5 Kg/m^2
Supercapacitor, Voltage	56V
Battery, Voltage	48V

C

CONCLUSION

A simulation for the prototype of Regenerative Braking System of an EV with supercapacitor- battery energy storage has been done in MATLAB Simulink. Regenerative Braking helps to earn some extra driving miles by exploiting the generator operation of motor and boost operation of motor driver inverter. To attain smooth braking Fuzzy logic controller is used for braking force distribution and PI controller is for controlling the braking current. The sequels are verified with the help of simulation results.

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