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A Novel Energy Regeneration Technique in Brushless DC Motors for Automobile Applications

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***Abstract*— The Regenerative braking is a very important topic of research in present scenario. The regenerative braking can improve the energy usage efficiency and can prolong the driving distance of Electric Vehicles (EV). In this work, a creative Regenerative Braking System (RBS) is proposed for the brushless DC motor. The traditional Proportional Integral Derivative (PID) control is very popular in electric car control, but it is difficult to obtain a precise brake current. Hence combining the Fuzzy Logic Control (FLC) along with PID can distribute the electrical braking force dynamically. Braking force is affected by factors like state of charge of battery, speed, and applied braking force which are chosen as fuzzy control input variables. In this work, PID is used to control constant brake torque by controlling the current and FLC is used for distribution of braking force. Under the assurance of braking safety and stability, this strategy distributes the regenerative braking force reasonably during braking. The speed of motor, SOC and motor DC bus current is analysed under the environment of MATLAB/ Simulink. The simulation results show that fuzzy logic and PID control can realize the regenerative braking and prolong the driving distance of EV ensuring quality of braking**

***Index Terms*—BLDC, Fuzzy, Electric Vehicles, PID control.**

I. INTRODUCTION

Nowadays Electric Vehicles (EV) are attaining more attention than conventional Internal Combustion Engine vehicles (ICE). These ICE vehicles use fossil oil as fuel which leads to the focus of environmental aspects and economic anxieties. The electric vehicles are hopeful substitute to ICE vehicles by the emerging technology of motor and battery. Electric Vehicle's performance features have become comparably better than that of ICE vehicles. It is impossible to recycle the brake energy by Regenerative Braking System (RBS) in ICE vehicles. So the idea proposed is on Regenerative braking of Brushless DC (BLDC) motors used in electric vehicles. When the vehicle's brake is pressed, the motor will operate as generator and the electrical energy is fed back to the battery instead of being wasted. During braking the vehicle's inertia pressures the motor into generator mode. The RBS applied to Electric Vehicles can lengthen the driving distance of the vehicle to the range of 16 % compared to the EVs without RBS. But the regenerative braking cannot be worked at all periods. Because when the battery is fully charged the energy is dissipated in resistive load so the braking is affected. Hence Electric Vehicles still needs mechanical brake for safety actions. Thus the smooth change over from regenerative braking to mechanical is done in a single foot pedal which cannot attain by conventional ICE vehicles.

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II. PROCEDURE FOR PAPER SUBMISSION

A. Brushless DC Motors: Construction and Working

A brushless DC (BLDC) motor is a rotating electric machine, where the stator is a classic 3-phase stator like that of an induction motor, and the rotor has surface-mounted permanent magnets. A brushless DC motor is defined as a permanent synchronous machine with rotor position feedback. In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary [1].

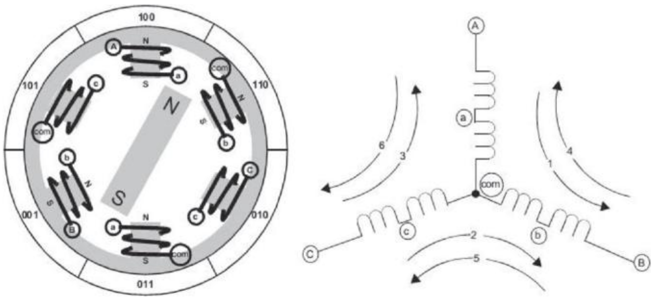

Figure 1 : BLDC motor construction

In the DC commutator motor, the current polarity is altered by the commutator and brushes. However, in the brushless DC motor, polarity reversal is performed by power transistors switching in synchronization with the rotor position. There are two control techniques are incorporated in a BLDC motor: Sensor control and sensorless control [2]. Sensor control uses Hall Effect sensors to achieve the commutation sequence.

B. Regenerative braking by MOSFET control

When you submit your final version, after your paper has been accepted, prepare it in two-column format, including figures and tables. Regenerative braking can be achieved by the reversal of current in the motor-battery circuit during deceleration, taking advantage of the motor acting as a generator, redirecting the current flow into the supply battery.

However, with the low speed of the BLDC motor, the winding back EMF cannot reach the voltage across the battery. Moreover, the recovery of energy also cannot be achieved. Due to the presence of inductances in motor windings, these inductances in the motor can constitute the boost circuit. In order to achieve the recovery of energy, we have to raise the voltage on the dc bus through the inductor accumulator.

We turn off all MOSFET on the high arms of H-bridge and control the low arms of H-bridge with PWM. Figure shows the phase relation among the back EMF, the armature current of the BLDC motor, and the switching signals for the bidirectional dc/ac converter, in which there is only one power switch operated within each commutation state. By controlling MOSFET, the whole circuit constitutes a boost circuit.

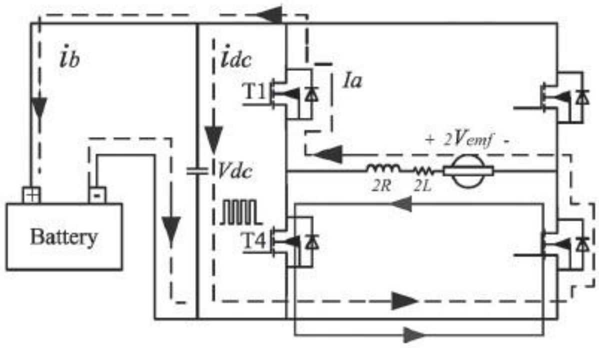

Figure 2: Equivalent Circuit of Single Switch Operation

III. Control Strategy of Regenerative Braking

Through the pedal sensor, we can obtain the driver's required braking force. According to the distribution regulations of braking force among front and rear wheels, the front braking force and the rear braking force can be calculated, respectively. According to the fuzzy logic controller, we can obtain the value of the regenerative braking force. Then, the front mechanical braking force, the regenerative braking force, and the rear braking force can be attained. At last, the regenerative braking force is translated into braking current through the relation:

$$I_{com} = k_1 \times F_{reg}$$

i.e., the braking current I_{com} is proportional to the regenerative braking force F_{reg}, and k_1 is the scale factor.

In RBS of EVs, the braking force is mainly the front-wheel braking force F_{front} and rear-wheel braking force F_{rear}. For the front-wheel drive EVs, the front-wheel braking force is composed of two parts: front wheel frictional braking force and regenerative braking force. Therefore, brake force distribution refers to total braking force $\sum F$ in the allocation of front and rear wheels, rear-wheel friction, and regenerative braking force distribution and co-ordination issues[7].

Such as vehicle speed, the driver's braking requirements and battery limitations etc. will influence the value of the regenerative braking force. Vehicle speed and the driver's braking requirements have large impacts on braking safety and battery limitations which are battery quantity and the maximum permissible charging current play important roles in protecting them from damage. The quantity of the batteries can be obtained from the batteries' SOC.

The relationships between the influence factors and the regenerative braking force are as follows:

i. *Relationship between batteries SOC and the regenerative braking force:*
When batteries' SOC is lower than 10%, the inner resistance of the batteries performs great value and unsuitable to be charged, so at this time, the proportion of the regenerative braking force should be low; when the value of SOC is from 10% to 90%, the batteries can be charged with big current and the proportion of the regenerative braking force should be increased correspondingly; when SOC is bigger than 90%, the charging current should be decreased to prevent deposit of lion and the value of regenerative braking force should be low, too.

ii. *Relationship between vehicle speed and the regenerative braking force:*
Vehicle speed plays an important role in ensuring braking safety and we should take the influence of the vehicle speed to the regenerative braking force into consideration. When speed is low, to ensure the braking safety and satisfy relevant regulations, the regenerative braking force should takes low proportion; when speed is middle, the regenerative braking force can increases to a proper high level; when speed is high, we can increase the ratio of the regenerative braking force to the biggest value.

iii. *Relationship between required braking force and regenerative braking force:*
The drivers braking requirements are concerned with the driving safety. The value of braking force represents the braking distance and time the driver requires. If the braking force is large, it means the vehicle should be stopped in short distance and a little time. At the time, we should decrease the proportion of regenerative braking force; when the braking force is middle, the ratio of the regenerative braking force taking should be increased; and at the last condition, the braking force is small, we can apply a large regenerative braking force to the vehicle.

IV. Implementation of Control Techniques

A. Fuzzy Logic Variables and Rules

Because Braking force distribution in EVs with

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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[5]. The application of Fuzzy is as follows:

The input variables are given as membership functions. A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is sometimes referred to as the universe of discourse, a fancy name for a simple concept.

From the above sections, we prefer four inputs of the fuzzy logic controller including batteries' temperature, SOC, vehicle speed and required braking force. The output is the regenerative braking force feeding into the machine [8].

a. Vehicle speed:

We prefer the set of speed as: {low; middle; high} and the universe of discourse is [-10; 1000]. The membership functions can be seen in Figure 5.14.

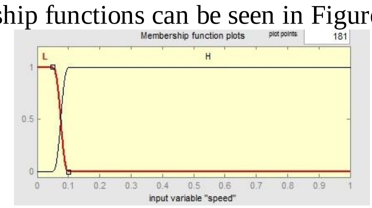

Figure 3: Vehicle Speed Membership Function

b. Required braking force:

We prefer the concourse of braking force as {low; Middle; High} and the universe of discourse is [-10; 2000] shown in figure 4.

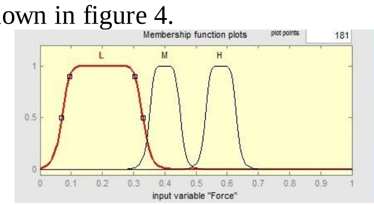

Figure 4: Braking Force Membership Function

c. SOC:

We prefer the set of SOC as: {low; middle; high} and the universe of discourse is [0; 1]. The membership functions are showed in Figure 5.

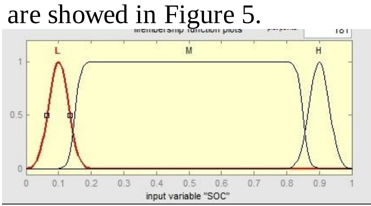

Figure 5 : SOC Membership Function

The output membership function is visualised in Fuzzy logic designer and is shown in Figure.6. Fuzzy control rules: the front braking force is L, M, and H; SOC is L, M, and H; and speed is L and H.

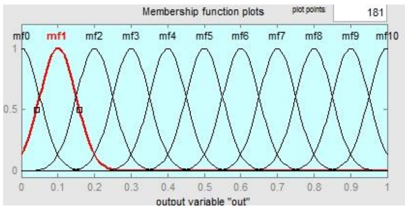

Figure 6: Output Membership Function

The rules adapted in Fuzzy logic controller in distribution of braking force is given in the Table I.

Table 1: Fuzzy Control Rules

Speed	SOC	F_{front}	MF	Speed	SOC	F_{front}	MF
L	L	L	2	H	L	L	5
L	L	M	1	H	L	M	5
L	L	H	0	H	L	H	4
L	M	L	4	H	M	L	10
L	M	M	2	H	M	M	9
L	M	H	3	H	M	H	8
L	H	L	3	H	H	L	5
L	H	M	1	H	H	M	3
L	H	H	2	H	H	H	1

B. *PID Control*

With Proportional Integral Derivative (PID) control used primarily to ensure a constant brake torque, different braking force values will give different PWMs. It is supposed that PID control can quickly adjust the desired PWM in order to maintain braking torque constantly [6].

A constant electrical braking torque can be achieved during the fuzzy inference. When the fuzzy reasoning is slower than PID control, the braking torque can be real-time controlled by PID control.

V. Simulation and Experimental Analysis

The electromechanical torque produced by the motor is fed into the vehicle subsystem to propel the vehicle. The modelling of the EV has been done in MATLAB/ Simulink. The driver block makes a torque request which propagates through various power train system component and realizes vehicle motion. System-level simulators have been modelled by using empirical data that are based on measurements supplied by component manufacturers or extended from measurements obtained from literature sources. These are modelled in Simulink as look-up tables. Other component models are physical or analytical in nature and are modelled by mathematical equations.

A. *Open Loop Simulation*

The open loop simulation model is shown in figure 7. The switching scheme is based on PWM control technique. The switching scheme for motoring and braking was simulated separately.

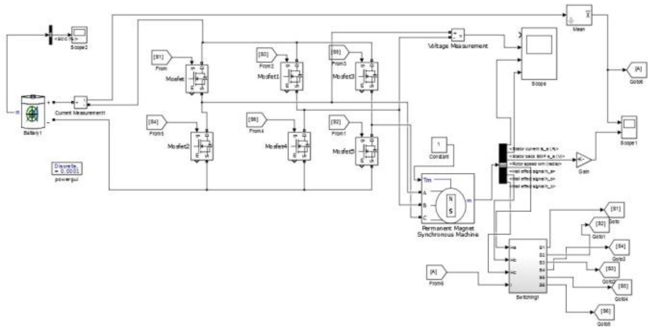

Figure 7: Open Loop Simulation

The driver block delivers the desired drive torque and the desired brake torque through the activation of the accelerator and brake pedal, respectively. If the driver wishes to accelerate the vehicle, he depresses the accelerator amount of depression of the accelerator pedal, a corresponding driver torque request is sent to the vehicle through various power train systems such as the battery and motor models.

The regeneration starts only when the brake pedal is pressed. Then, the brake torque due to the regenerative brake control strategy is divided into regenerative braking and friction braking.

Open loop simulation is performed by applying motor parameters on Permanent Magnet Synchronous Machine for trapezoidal back EMF. Motor parameters are provided to achieve rated speed of 4000 rpm. Switches used are MOSFETs because of its performance for high power applications and lower turn on and of losses.

The switching schemes are simulated using logic gates by separate subsystems. The output are evaluated by viewing speed of the motor, State of charge of the battery (SOC) and the DC bus current of battery. The waveforms are shown in Figure. 8.

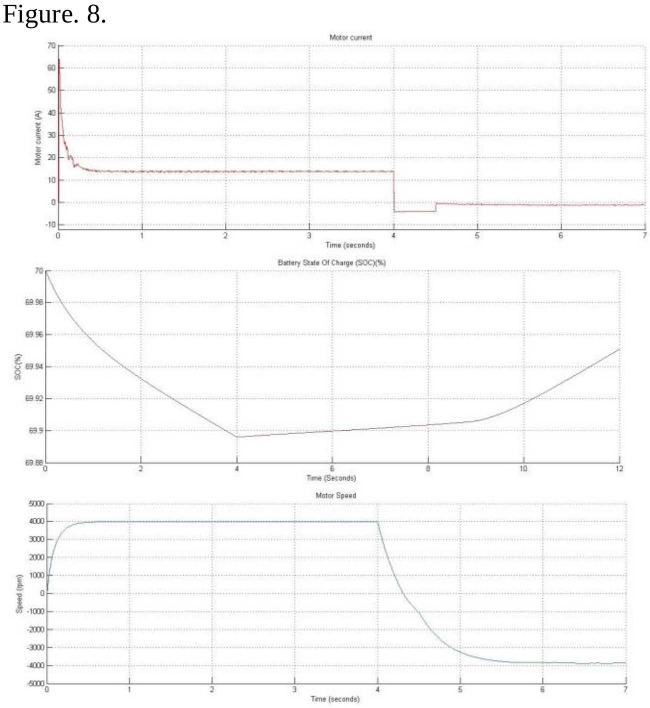

Figure 8: a) DC link Current of the Motor, b) State of Charge of Battery c) Speed of the Motor

The machine attains the rated speed on a gradual manner and reaches the rated value. Machine continues running at the rated rpm so long the motoring pulse is applied. The pulse for the motor control circuit is removed for a 0.5 seconds duration. At that time the speed starts reducing and reaches zero speed. Taking the advantage of motor running as a generator, i.e. the motor running in the reverse direction, regenerative braking switching signal is applied to the motor control circuit.

The motor current drops down to a negative value, while operating under no control over the current. Current sustains at that level as long as no switching pulse is applied. When the regenerative switching scheme is applied, the current reaches a negative constant value and settles there. This region is where the regenerative braking occurs and is analysed by examining the State Of Charge (SOC) of battery.

On the application of braking scheme, it is observed that the battery SOC rises gradually to a greater proportion indicating the recovery of energy.

B. Closed Loop Simulation

The closed loop simulation is achieved by controlling the output torque by PID control and distribution of braking force by using Fuzzy logic Controller. PID tuning technique is used to maintain a constant output current. Hence output torque is maintained at a constant level by controlling current

$$T_a = K_a I_a \quad (1)$$

Where Ta is the torque, K_a is the torque constant and I_a is the armature current. Simulink model of closed loop control is shown below. The closed loop speed, SOC, DC bus current are analysed on the basis of application of intermittent braking scheme applied on the Permanent Magnet Synchronous Motor system. Different values of brakes are applied at a fixed period of time and the waveforms are evaluated.

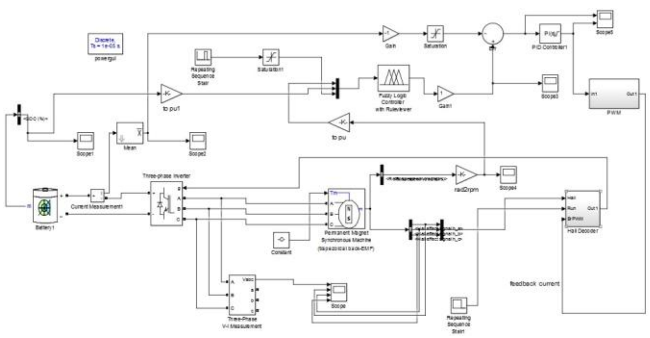

Figure 9: Closed Loop Simulation

The speed waveform in Figure.10 confirms the occurrence of intermittent braking on subsequent time intervals. A constant amount of braking is applied to verify the operation of the system under the designed operating conditions.

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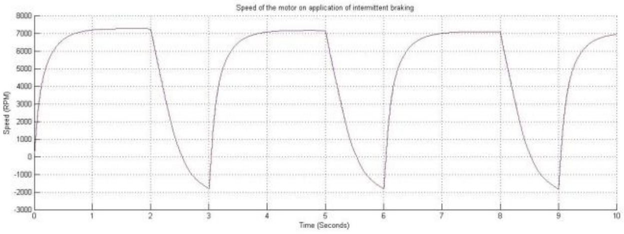

Figure 10: Speed of Motor in Closed loop

The controlled current in the DC bus side of the motor terminals shown in Figure.11 shows that the current during braking is controlled to maintain a constant torque at the output of the motor shaft. On application of braking, the current without showing any irregularities sustains in a constant value under the effect of PID control.

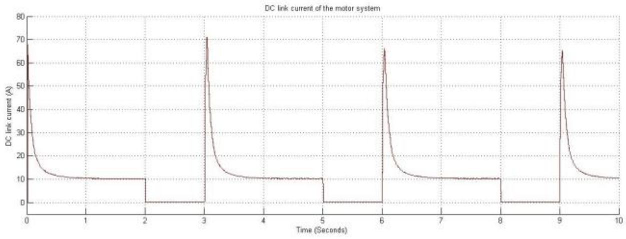

Figure 11: DC Link Current in Closed loop

The State of charge of the battery (Figure.12) is evaluated to verify the recovery of energy during the regenerative braking mode of operation. At the period of application of braking scheme, the output mechanical power is recovered back into a smaller proportion indicating the effective mode of operation.

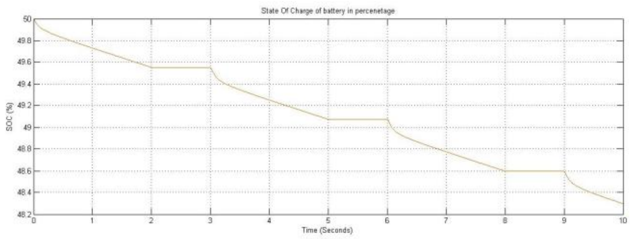

Figure 12: Battery SOC

VI. Conclusion

A new control concept for BLDC machines for Electric vehicles has been introduced. The proposed method has proved as an efficient method of Regenerative Braking System of EVs. The performance of the EVs regenerative brake system using the proposed control strategy is evaluated through MATLAB/ Simulink environment. PID control which is very popular method in electric car control has the difficulty of obtaining the precise brake current. So by combining Fuzzy control and PID control methods RBS can distribute the electrical braking force dynamically. Braking force is affected by many factors such as SOC, speed and brake strength and these factors are effectively analyzed using the two techniques used.

It has been verified that the proposed technique improved the efficiency of the system by increasing the percentage of rise of the Battery State of Charge (SOC) by 0.05%. Also maintains the torque output at a reasonable value for safe and stable driving by removing torque ripples during the regenerative mode. This confirms the effectiveness of combined operation of Fuzzy and PID in the operation of BLDC motor in Electric vehicle applications.

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