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A Novel Energy Regeneration Technique in Brushless DC Motor for Electric Vehicles

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Abstract: ***Regenerative braking can provide better energy usage efficiency and can extend the driving distance of electric vehicles (EVs). An imaginative regenerative braking system (RBS) is offered in this paper. The RBS is modified to brushless dc (BLDC) motor, and it emphasize on the sharing of the braking force, as well as BLDC motor control. 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 paper, BLDC motor control utilizes the PID control, and the sharing of braking force adopts FLC. The simulation results are analyzed under the ENVIRONMENT of MATLAB and Simulink. The simulation results show that the fuzzy logic and PID control can realize the regenerative braking and can extend the driving distance of EVs under the condition of ensuring braking quality.***

Keywords: BLDC Motor, Fuzzy Control, PID control, Electric Vehicle.

1. Introduction

In recent years electric vehicles plays an very important role in our daily life so that our life goes easy. Electric vehicles are normally receiving much attention as compared to the hybrid electric vehicles and ICE (internal combustion engine) vehicles. The development of EV's becoming more popular in small as well as large cities due to the global warming and also rise in petrol and diesel prices. 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 RBS in ICE vehicles. So the idea proposed is on Regenerative braking of BLDC motors used in electric vehicles.

Regenerative braking is the process of feeding energy from the drive motor back into the battery during the braking process, when the vehicle's inertia forces the motor into generator mode. In this mode, the battery is seen as a load by the machine, thus providing a braking force on the vehicle [2]. 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. At low speeds regenerative braking is not effective and may fail to stop the vehicle in the required time, especially in an emergency. A mechanical braking system is also important in the event of an electrical failure [3].

2. BLDC Motor and its Control

2.1 Brushless DC Motors: Construction and Working

BLDC motors also known as Electronically Commutated Motors (ECMs) are synchronous motors that are powered by DC electric source through an integrated inverter/switching power supply, which produces an Alternating Current (AC) electric signal to drive the motor. Additional sensors and electronics control the inverter output amplitude waveform and frequency. These are ideally suitable for EVs because of their high power densities, low maintenance, and high efficiency.

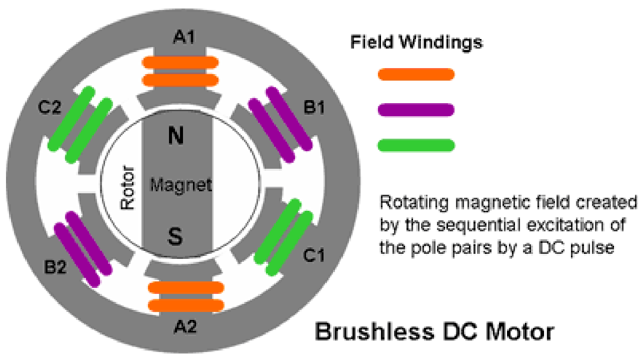

Figure 1: BLDC Motor

A 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. BLDC motor is a type of synchronous motor. It means that the magnetic field generated by the stator and the rotor rotation are at the same frequency [4]. BLDC motors do not experience the "slip" which is normally seen in induction motors. As shown in Figure. 1, in a BLDC motor, permanent magnets are mounted on the rotor, with the armature windings being fixed on the stator with a laminated steel core. BLDC motor parts are as shown in Figure. 2.

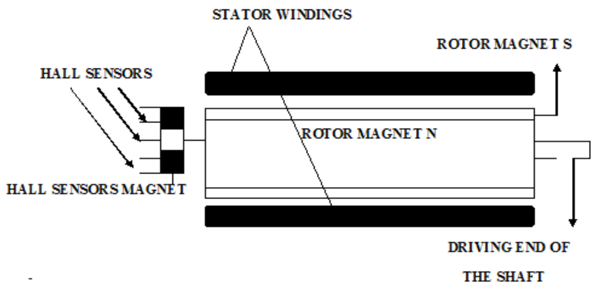

Figure 2: Parts of BLDC Motor

2.2 BLDC Motor Control

In brushless motor, the commutation is achieved electronically by controlling the conduction of switches in the arm of inverter. To control the BLDC motor the position of rotor must be determined which decides the commutation. Hall Effect sensors are the most common sensor for estimation the rotor position. The hall signals are given to the controller which generates gate signals. These Pulse Width Modulation (PWM) signals are given to the switches in the inverter which supplies the stator winding.

The basic drive circuit for a BLDC motor is shown in Figure. 3. Each motor lead is connected to high-side and low-side switches. The correlation between the sector and the switch states is noted by the drive circuit firing. At the same time, each phase winding will produce a back EMF. A number of switching devices can be used in the inverter circuit, but MOSFET and IGBT devices are the utmost common in high power applications due to their low output impedances.

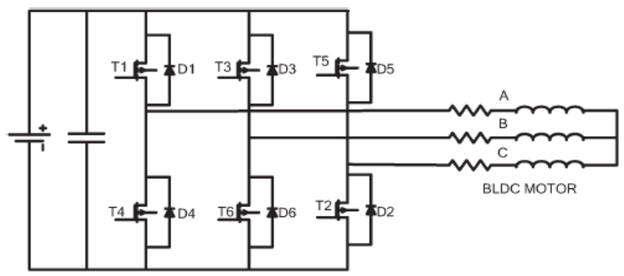

Figure 3: H-bridge Inverter Circuit

3. Regenerative Braking System

3.1 Working Principle

In normal supply system, when the machine generates the power, the terminal voltage of the machine rises. The generated power flows to the load, which is connected to the supply and the source is pleased from supplying the lot of amount of power to the load. When loads are connected to the supply line and they are in need of power, which is more or equal to the regenerated power then regenerative braking is possible. The load capacity is less than the regenerated power, all the regenerated power which is generated will not be absorbed by the load. Thus remaining power will be supplied to capacitor in supply line. Thus excess power is diverted to resistance or super capacitor bank, thus it will dissipated as heat energy. The mention energy will generated only when source is battery, the regenerated energy will be stored in the battery. The regenerative power flow direction shown in the figure.4, the motoring mode, in motoring mode the power flows from battery to motor and motor runs in the clockwise direction.

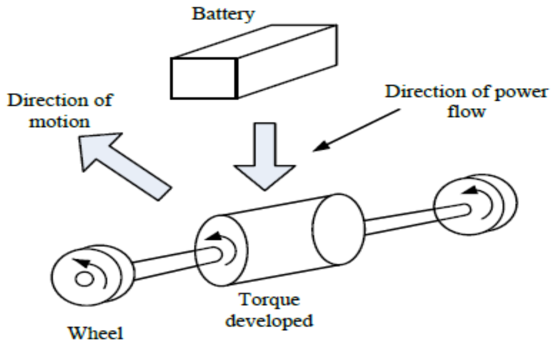

Figure 4: Normal Motoring Mode

When we apply the brake to the motor the power generated is regenerative power and the generated power is save in the battery again, and the battery which is connected parallel to capacitor. This power goes to battery and remaining power goes to capacitor, thus the charging capacity of battery increases and the figure.5 shows the braking mode.

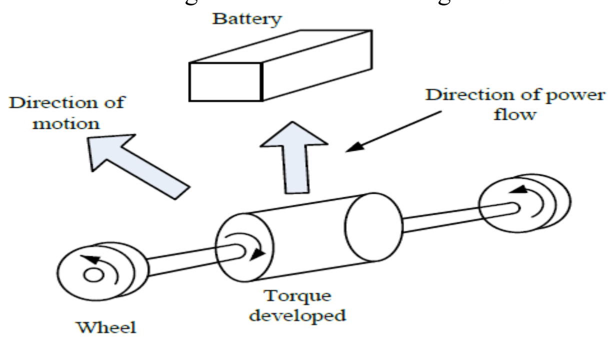

Figure 5: Normal Braking Mode

3.2 Control of Inverter Switches for Regenerative Braking Modes

During deceleration the current in the circuit of motor-battery is reversed to attain regenerative braking. PWM control is implemented for an active braking control. The back EMF of the stator winding is incapable to reach the voltage across battery when the speed of BLDC motor is low. The inductances in the stator of motor can establish a boost circuit. 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.T1, T3, T5 are higher arm switches which are always kept off. T4, T6, T2 are lower arm switches which are controlled for the power reversal during regenerative braking. The equivalent circuit of a single switch is shown is figure. 6

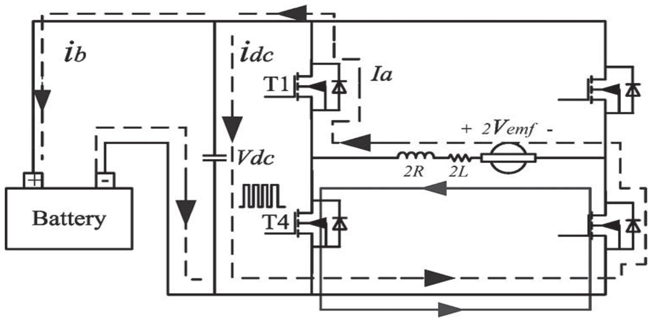

Figure 6: Circuit of single switch during regenerative braking

During normal motoring mode the control is done by operating the switches in accordance with the hall sensor signals as shown in Table I. It shows that during motoring mode both upper arm and lower arm switches are used. The point to be noted here is simultaneously both the switches in the single arm of the inverter cannot be operated.

Table 1: Switching Pattern for the Motoring Mode

H1	H2	H3	***S1***	***S2***	***S3***	***S4***	***S5***	***S6***
1	0	1	0	1	0	1	0	0
1	0	0	1	1	0	0	0	0
1	1	0	0	0	0	1	0	1
0	1	0	1	0	0	0	0	1
0	1	1	0	1	0	0	0	1
0	0	1	0	1	1	0	0	0

During braking mode the motor operates as generator. The energy reversal between motor and battery can be done by operating only the lower arm switches. Table II shows the switching pattern for the regenerative braking mode in accordance with the corresponding Hall signals. In this only the lower arm switches are controlled all the upper arm switches of the inverter are kept off for all Hall signals.

Table 2: Switching Pattern for the Braking Mode

H1	H2	H3	S1	S2	S3	S4	S5	S6
1	0	1	1	0	0	1	0	0
1	0	0	1	0	0	0	0	1
1	1	0	0	0	1	0	0	1
0	1	0	0	1	1	0	0	0
0	1	1	0	1	0	0	1	0
0	0	1	0	0	0	1	1	0

4. Electric Vehicle Modeling

Electric vehicle plays a major role to reduce global warming and keeps the people healthy. In many developing countries like India petroleum is imported at very large scale and very high subsidy is provided by government to the people, which cause losses of economical growth. The modeling of the EV has been done in MATLAB/ Simulink.

4.1 Driver Subsystem

Driver block delivers desired drive torque and the desired brake torque through the accelerator and brake pedal, respectively. If the driver wishes to accelerate the vehicle, he depresses the accelerator. Depending on the amount of depression torque request is sent to the vehicle through various power train systems. Regeneration starts only when the brake pedal is pressed. Once the brake pedal is depressed, a corresponding proportion of brake torque is applied. Then, the brake torque is divided into regenerative braking and friction braking [5]. The amount of mechanical energy consumed by a vehicle when driving a pre specified driving pattern mainly depends on three factors: the aerodynamic friction losses, the rolling friction losses, and the energy dissipated in the brakes. The elementary equation that describes the longitudinal dynamics of a road vehicle has the following form:

$$m_v \frac{dv(t)}{dt} = F_t(t) - F_a(t) - F_r(t) - F_g(t) \qquad (1)$$

Where *mv* is the vehicle mass (in kilograms), *v* is the vehicle speed (in meters per square second), *Fa* is the aerodynamic friction (in Newton), *Fr* is the rolling friction (in Newton), and *Fg* is the force caused by gravity when driving on non horizontal roads (in Newton). The traction force *Ft* is the force generated by the prime mover minus the force which is used to accelerate the rotating parts inside the vehicle and then minus all friction losses in the Power train.

A) Aerodynamic Friction Losses

Usually, the aerodynamic resistance force *Fa* is approximated by simplifying the vehicle to be a prismatic body with a frontal area *Af*.

$$F_a(v) = \frac{1}{2}\rho_a A_f C_d v^2 \qquad (2)$$

Here, *v* is the vehicle speed (in meters per square second), and *ρa* is the density of ambient air (in kilograms per cubic meter). The parameter *Cd* is the coefficient of drag estimated using computational fluid dynamics programs.

B)Rolling Friction Losses:

The rolling friction is modeled as,

$$F_r = C_r m_v g \cos(\alpha) \qquad (3)$$

Where *mv* is the vehicle mass (in kilograms), *g* is the acceleration due to gravity (in meters per square second), *Cr* is the rolling friction coefficient, and *α* is the slope angle (in degrees). The rolling friction coefficient *Cr* depends on many Variables. The most important influencing quantities are vehicle speed *v*, tire pressure *p*, and road surface conditions. For many applications, particularly when the vehicle speed remains moderate, the rolling friction coefficient *Cr* may be assumed to be constant.

C) Uphill Driving Force:

The force induced by gravity when driving on a non horizontal road is conservative and considerably influences the vehicle behavior. In this paper, this force will be modeled by,

$$F_g = m_v g \sin(\alpha) \qquad (4)$$

5. Control Strategy of Regenerative Braking

Through the pedal sensor, we can obtain the driver's required braking force. According to the fuzzy logic controller, we can obtain the value of the regenerative braking force.

Regenerative braking force is translated into braking current through the relation:

$$I_{com} = k_1 * F_{reg} \quad (5)$$

i.e., braking current Icom is proportional to the regenerative braking force Freg, and k1 is the scale factor.

In RBS of EVs, the braking force is mainly the front-wheel braking force and rear-wheel braking force. 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 ΣF in the allocation of front and rear wheels, rear-wheel friction, and regenerative braking force distribution and co-ordination issues [6].

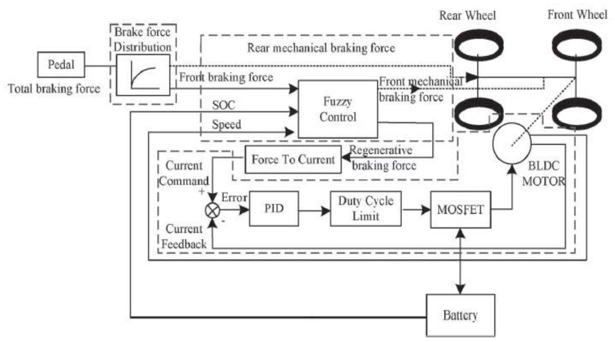

Figure 7: Structure of Control Strategy

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:

1) 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 li-ion and the value of regenerative braking force should be low, too.

2) 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.

3) 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.

6. Implementation of Control Techniques

6.1 Fuzzy Logic Variables and Rules

Braking force distribution in EVs with 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 [7].

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.

We prefer three inputs of the fuzzy logic controller SOC, vehicle speed and required braking force. The output is the regenerative braking force feeding into the machine [8]. We prefer the set of speed as: {low; middle; high} and the universe of discourse is [-10; 1000]. Braking force as {low; Middle; High} and the universe of discourse is [-10; 2000].SOC as: {low; middle; high} and Universe of discourseis[01].Ratioas$\{MF0, MF1, MF2, MF3, MF4, MF5, MF6, MF7, MF8, MF9, MF10\}$=(0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0).

The rules in FLC in the distribution of braking force are given in the Table III.

Table III: Fuzzy Control Rules

SPEED	***SOC***	$F_{(front)}$	***MF***
L	L	L	2
L	L	M	1
L	L	H	0
L	M	L	4
L	M	M	2
L	M	H	3
L	H	L	3
L	H	M	1
L	H	H	2

SPEED	*SOC*	$F_{(front)}$	*MF*
H	L	L	5
H	M	M	5
H	H	H	4
H	L	L	10
H	M	M	9
H	H	H	8
H	L	L	5
H	M	M	3
H	H	H	1

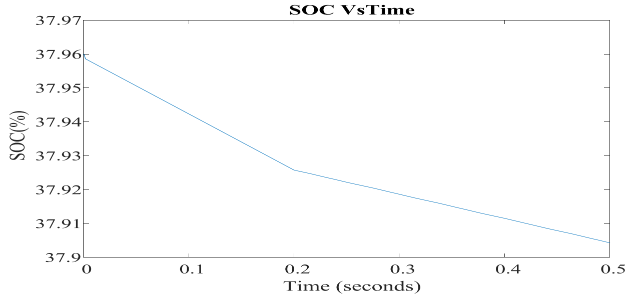

Figure.10: SOC of the Battery

6.2 PID Control

With Proportional Integral Derivative 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.

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.

Simulation Results

With the above design consideration the simulation has been done and the result is presented here. Speed is set at 300rpm and load torque disturbance is applied at 0.2 sec and the braking is obtained at the set speed.

Vehicle speed plays an important role in ensuring the brake safety. Figure.8 shows the speed of motor. Therefore it reduces the back EMF induced in the armature. The generated back EMF is shown in Figure.9. The speed waveform confirms the occurrence of braking on subsequent time intervals. A constant amount of braking is applied to verify the operation of the system under the designed operating conditions.

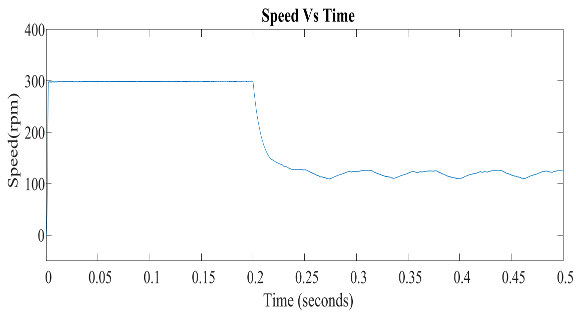

Figure 8: Speed of the motor

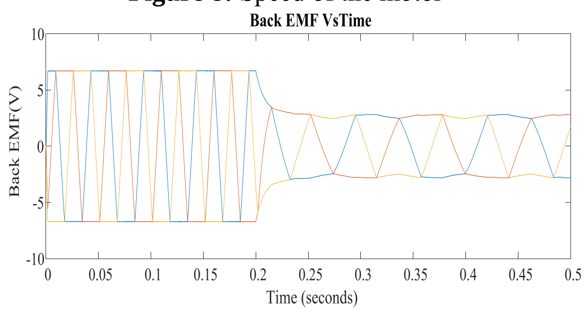

Figure 9: Back EMF of the Motor

Figure 10.shows the Battery State Of Charge (SOC) which reduces during the braking. When the battery's SOC is below 10%, which is unsuitable for charging. When the SOC is between 10% and 90%, the battery can be charged with a large current. When the SOC is above 90%, the charging current is reduced to prevent the excessive charging of the battery.

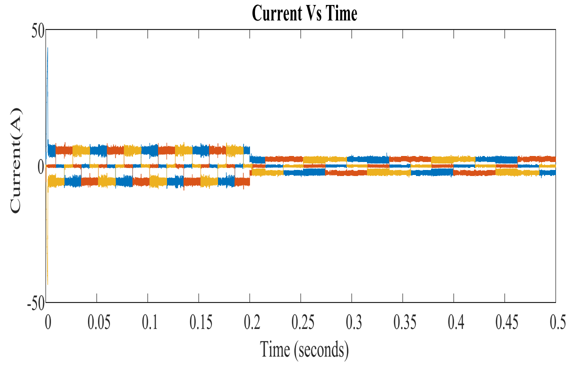

Figure 11: Current of the Motor

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 sustains in a constant value under the effect of PID control.

Table 1V: BLDC Motor Specification

Symbol	*Parameter*	*Value*
R	Phase resistance	0.18(ohm)
L	Phase inductance	0.835(Mh)
Ke	Back EMF constant	3.86(V/rad/s)
Kt	Torque constant	36.8(mNm/A)
P	Pole pairs	4
Jm	Rotor inertia	.00062(kgm^2)
T	Peak torque	154(mNm)
Vdc	Rated voltage	72(volt)

Table V: Electric Vehicle Parameters

Symbol	Parameter	Value
Cd	Aerodynamic drag coefficient	0.5
ρ_a	Ambient air density	1.2258(Kg/m3)
Cr	Rolling friction coefficient	0.0112
Mv	Vehicle weight	250kg
Rt	Radius of tyre	0.287m
Af	Frontal area	2.43m2
α	Max climbing angle	0
v	Vehicle speed	25kmph

7. 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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