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Maximum Energy Recovery in Electric Vehicle through Regenerative Braking System

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***Abstract:** In a world in which renewable energy has a very high penetration, Electric vehicle is starting to take over the automotive industry and reach an inflection point. Advances in battery technology and significant improvement in electric motor efficiency have made electric vehicles an attractive alternative, especially for short distance commuting. This driving range of electric vehicle greatly restricts the development of EVs. Hence to increase the range for electric vehicle, energy conservation is the hour of need. This energy conservation can be achieved through Regenerative Braking System. The main aim of this paper is to develop a regenerative braking model that stores the energy which is usually lost in braking, and reuse it. The use of regenerative braking system in automobiles provides us the means to balance the kinetic energy of the vehicle to some extent which is lost during the process of braking. This paper deals with the use of BLDC motor as a receiver for kinetic energy to convert the mechanical energy into chemical energy and store it in battery. A Brake force distribution strategy is opted to increase the stability of the vehicle because of negative toque acting on the wheels. Simulation models have been created in MATLAB/Simulink software and relationship curves of braking speed, braking deceleration, braking distance, state of charge SOC, braking energy, recycling energy and efficiency of this system is analysed for different conditions.*
***Keywords**: Regenerative Braking System, BLDC motor, Energy recovery, Brake Force Distribution.*

I. INTRODUCTION

In recent times, electric vehicles (EVs) have received much attention as an alternative to traditional vehicles powered by internal combustion engines running on non-renewable fossil fuels. With the emission norms getting stricter, the EVs offer advantages such as no emissions and no pollution. But EVs still suffer from the main problem of short driving range. Regenerative braking serves as a solution to overcome this inconvenience.

Regenerative braking can be used in an EV as a way of recouping energy during braking, which is not possible in conventional IC engine vehicles. Regenerative braking is the process of feeding energy from the drive motor back into the battery during the braking process, where 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.

It has been known that the driving range of an EV can be increased up to 15%-25% with the use of regenerative braking.

Mechanical braking is still required in EVs for a number of reasons. At low speed regenerative braking is not effective and may fail to stop the vehicle in required time, especially in emergency. A mechanical braking system is also important in the event of an electrical failure i.e. in the case of regenerative braking failure, mechanical braking becomes critical.

It is common in electric vehicles to combine both mechanical braking and regenerative braking functions into a single foot pedal: the first part of the foot pedal controls regenerative braking and the final part controls mechanical braking. A toque command is derived from the position of the throttle pedal. The motor controller converts this torque command into the appropriate 3-phase voltage and current waveforms to produce the commanded torque (braking) in the motor in the most efficient way.

This braking toque produced is the source of negative torque which when applied to the rear wheels can cause a car to become unstable. Hence, Brake force distribution is used to limit the regeneration when car wheels starts to slip. Therefore, to increase the braking efficiency and braking stability of the electric vehicle there is a need for study on brake force distribution strategy between regenerative braking of motor and friction brake. In the paper, the optimized braking force strategy is proposed based on braking stability of the vehicle and the simulation models are established based on MATLAB/Simulink software.

II. BLDC MOTOR

This paper deals with the use of BLDC motor as receiver of the kinetic energy. Principally, a brushless DC (BLDC) motor is an inside-out permanent magnet DC motor, in which the conventional multi-segment commutator, which acts as a mechanical rectifier,

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is replaced with an electronic circuit to do the commutation. A BLDC motor has a *higher efficiency* and require *less maintenance* than a conventional DC motor with brushes. However, a BLDC motor requires relatively complex electronics for control.

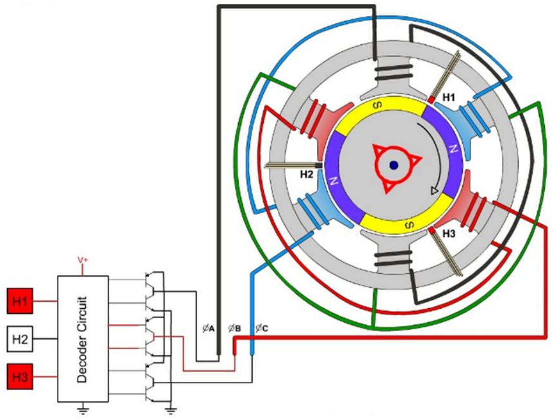

Fig. 1-Permanent Magnet BLDC motor construction

A BLDC motor requires a DC source voltage to be applied to its stator windings in a sequence so as to sustain rotation. This is done by electronic switching using an inverter as shown in Figure 2. The inverter circuit employs a half *H-Bridge* for each stator winding.

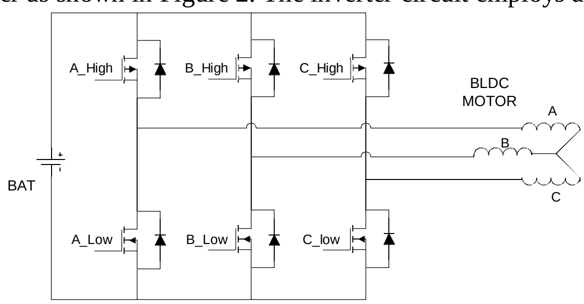

Fig. 2-BLDC motor circuit

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. *Independent switching* in conjunction with *pulse width modulation* (PWM) method is used in figure 2 circuit to implement an effective braking control.

In *Independent switching*, all top switches are kept *off* while the bottom switches are *on* for 120 degree portion of cycle.

PWM is used to control the level of regenerative braking by varying the *duty cycle* of PWM.

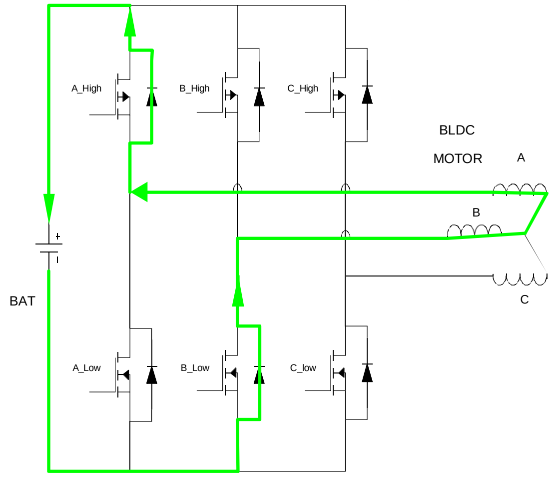

Fig. 3-Regenerative current flow

The switching steps are controlled by the control stage measuring the Hall Effect sensor readings, similar to the motoring process.

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III. DESIGN OF BRAKE FORCE DISTRIBUTION STRATEGY

To propose a brake force distribution strategy the electric vehicle selected in this paper is a front wheel drive, which is provided energy by single battery. The relevant parameters of electric vehicle are shown in Table 1.

PARAMETERS	VALUES
Total mass (m)	1200kg
Wheelbase (L)	2.34m
Wheel radius (r)	0.28m
Centroid height (h_g)	0.5m
Distance from centroid to front axle (a)	1.06m
Distance from centroid to rear axle (b)	1.28m
Main reduction ratio (i_0)	3.55
Maximum speed (u_a)	80km/h
Rated speed (N_e)	3000rpm
Rated power (P_e)	25kw
Rated torque (T_e)	90N-m
Peak rotational speed (N_{max})	5000rpm
Battery Peak power (P_{max})	45kw
Battery peak torque (T_{max})	200N-m
Rated total voltage (E)	324V
Rated capacity (Q)	100A-h

Table-1

The formula of ideal brake force distribution curve is as follows

$$F_{\mu 2}=\frac{1}{2}\left[\frac{G}{h_g}\sqrt{b^2+\frac{4h_gL}{G}F_{\mu 1}}-\left(\frac{Gb}{h_g}+2F_{\mu 1}\right)\right] \quad (1)$$

where, $F_{\mu 1}$ is the braking force of front wheel brake, $F_{\mu 2}$ is the braking force of rear wheel brake, G is the total weight of electric vehicle.

In order to ensure the braking stability of vehicle and its braking efficiency, ECE (Economic commission for Europe) has created some braking regulations. Its expression equation is as follows:

$$\begin{cases} F\mu 1=\frac{z+0.07}{0.85}\frac{G}{L}(b+zh_g) \\ F\mu 2=Gz-F\mu 1 \end{cases} \quad (2)$$

where, **z** is the braking strength. Based on the ECE regulations and curve of ideal braking force distribution, the optimized brake force distribution strategy suggested is shown in figure 4.

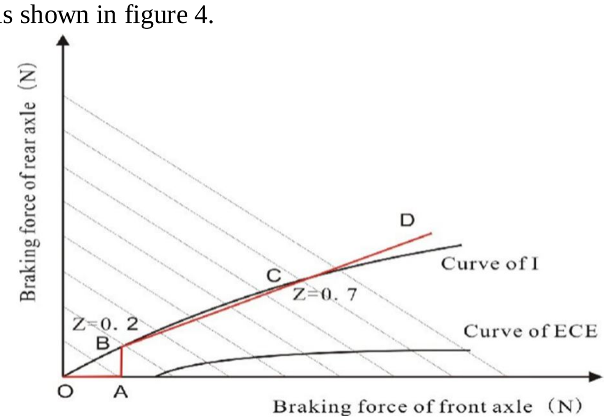

Fig.4-Optimized Distribution strategy

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It is known from brake force distribution curve [1] when the commanded deceleration (represented by the braking pedal position) is less than 0.2 g, only regenerative braking on the front wheels is applied and when greater than 0.2 g, the braking forces on the front and rear wheels follow the ideal brake force distribution curve I.

So, within line segment OA the strength of braking force is greater than zero and less than 0.107(calculated by the maximum braking force provided by the motor i.e. 1268N, and the corresponding braking strength is 0.107). So all the braking force is provided by front axle.

Within line segment AB the strength of braking is greater than 0.107 and less than 0.18. This moment, because the motor can't provide all the required braking force, the electric vehicle is in the composite braking state. In order to make the front wheels of electric vehicle not to be locked on the road surface of low adhesion coefficient, the front axle is no longer applied friction braking force, the partial braking force which exceeds the maximum braking force of motor will be provided by friction brakes of rear axle.

Within line segment BC the strength of braking is greater than 0.18 and less than 0.7. So, the braking force follows the ideal braking force curve I. Within line segment CD the strength of braking is greater than 0.7, which belongs to the emergency braking state. At this time, in order to ensure the braking safety, the braking of electric motor is not involved in braking, and there is only mechanical friction brake on the electric vehicle.

The math formulas of different line segments of braking force of motor (F_e), braking force of front axle brake (F_f) and braking force of rear axle brake (F_r) are as follows.

$$\text{OA,} \begin{cases} F_e = Gz \\ F_f = Gz - F_e \\ F_r = 0 \end{cases} \qquad \textbf{(3)}$$

$$\textbf{AB,} \begin{cases} F_e = F_{emax} \\ F_f = 0 \\ F_r = Gz - F_e \end{cases} \qquad \textbf{(4)}$$

$$\textbf{BC,} \begin{cases} F_e = F_{emax} \\ F_f = \frac{(Gz-385.78)}{1.369} - F_e \\ F_r = Gz - F_e - F_f \end{cases} \qquad \textbf{(5)}$$

$$\textbf{CD,} \begin{cases} F_e = 0 \\ F_f = \frac{(Gz-385.78)}{1.369} \\ F_r = Gz - F_f \end{cases} \qquad \textbf{(6)}$$

IV. SIMULATION MODELS

The simulation model is developed in MATLAB/Simulink, which is carried out to be as close as to the real regenerative braking system. Target of these simulation is to analyze the regenerative braking process with focus on interaction of the two different braking system (mechanical and regenerative brake).

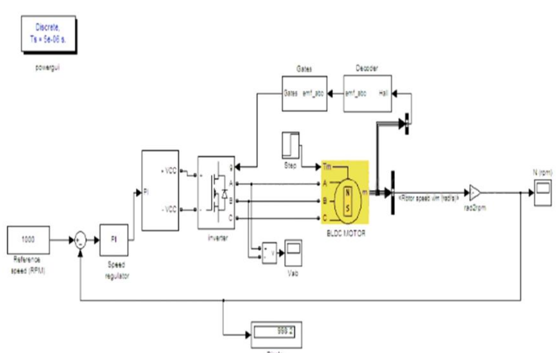

Fig.5- BLDC motor circuit

A model of BLDC motor is prepared in Simulink as shown in Fig.5 and efficiency of mechanical transmission is calculated based on the following formula:

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$$T_{max}=\begin{cases} T_e \text{ , } n \le N_e \\ \frac{9550}{n} \text{ , } n > N_e \end{cases} \quad (7)$$

where, n is speed of motor

$$F_{emax}=\frac{T_{max}}{r\,\eta} \quad (8)$$

where, η is the transmission efficiency

Here, T_{max} and F_{emax} is the maximum braking force and maximum braking torque of the motor.

A model of state of charge (SOC) of battery is created as shown in the Fig.6.

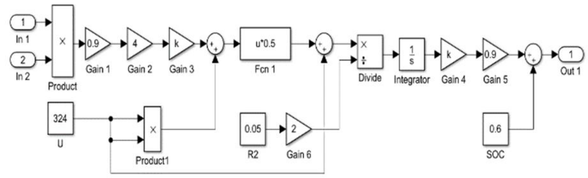


Fig.6- Model of Storage Battery

The model created is based on the following formulas:

$$P_b=U*I=U*(E-U)/R \quad (9)$$

where, P_b is charging power, U is charging voltage, I is charging current, and R is internal resistance of battery.

Here, U can be calculated by above equation:

$$U=\frac{E-\sqrt{E^2-4P_bR}}{2} \quad (10)$$

The calculation formula for SOC is as follows:

$$SOC=SOC_0+\frac{\eta_{charge}\int Idt}{Q_{ALL}} \quad (11)$$

Where, SOC_0 is the initial value of SOC, η_{charge} is the charging efficiency, and Q_{ALL} is the total power of battery.

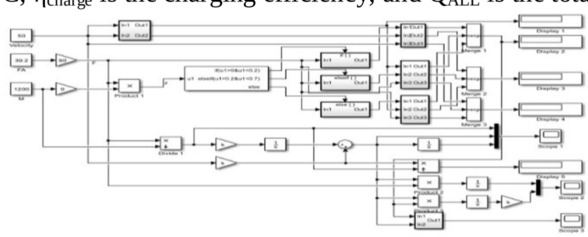
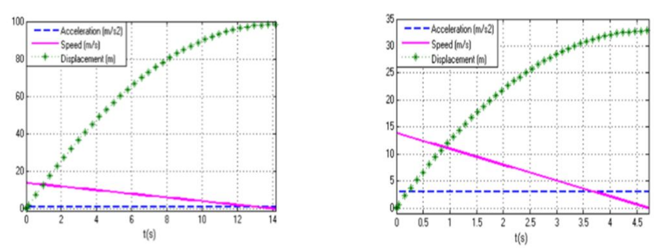


Fig.7- Overall Regenerative Braking System Model

A model of overall regenerative braking system is created and shown in Fig.7.

In this regenerative model, if else statements are used to generate the results for variable braking strength (z) value. According to these condition three different subsystems are created on the basis of (4, 5, 6) equations. Result for all these subsystems are merged and viewed on the scope.

V. RESULT AND ANALYSIS



(A) (B)

Fig.8- (A) when z=0.1, (B) when z=0.3

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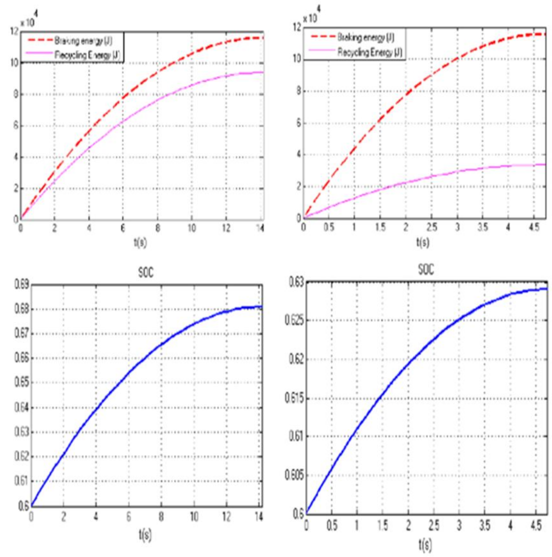
The relationship curves of braking speed, braking deceleration, braking distance, state of charge SOC, braking energy and recycling energy are shown in Fig.8 while keeping the initial velocity 50km/h with variable braking strength of 0.1 and 0.3. 0.3.

Parameter(z=0.1)	Values
Braking Time	14.1 sec
Braking Distance	100 m
Maximum SOC	0.68
Parameter(z=0.3)	Values
Braking Time	4.7 sec
Braking Distance	32.5 m
Maximum SOC	0.62

Table-2 Simulation Results

The above table and graphs shows that when higher braking strength is applied, the friction brakes participates in the braking process reducing the recovery energy and declining the SOC value. The bigger problem faced during the energy recovery is aerodynamic losses and rolling resistance offered by the vehicle, due to these losses energy dissipated can't be totally recovered leading its efficiency approximately around 64%.



VI. CONCLUSION

In this paper, the regenerative braking system has been studied and a model was designed and simulated in MATLAB/Simulink. The system efficiency was improved by using a commercial BLDC motor for precise electronic commutation. The system controls the flow of current during various stages of the cruise profile with the help of an Independent Switching strategy. Also a Brake force distribution strategy was implemented to provide better stability to the vehicle.

Simulation results for various braking strength showed that regenerative braking system has the ability to recover 15-25% of the total waste energy produced during braking.

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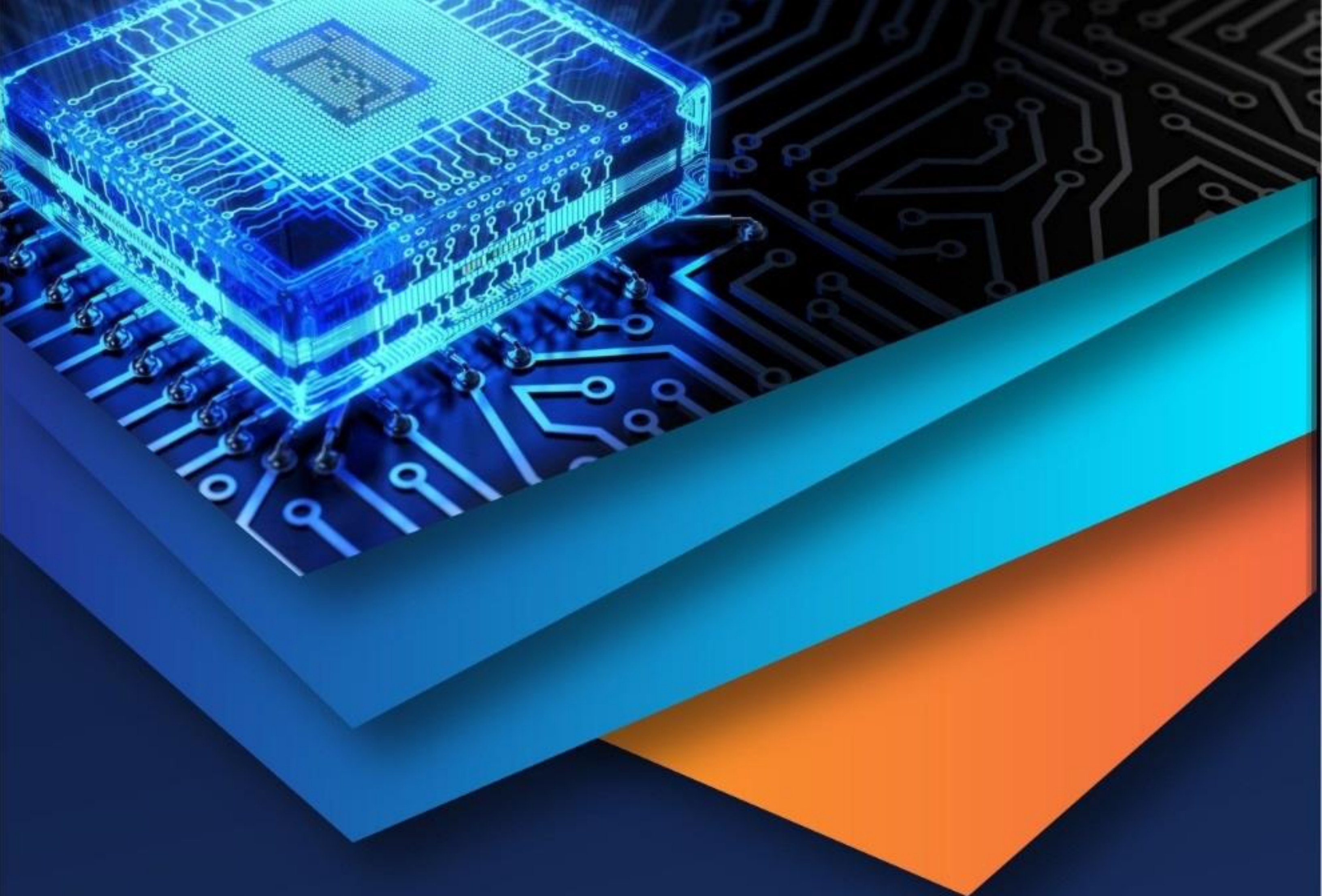

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