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A NOVEL ELECTRIC BRAKING METHOD FOR A BLDC MOTOR DRIVEN ELECTRIC VEHICLE.

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Abstract **:** In this paper a new electric braking system based on stopping time and energy regeneration is proposed for a brushless DC (BLDC) motor driven electric vehicle (EV). The new braking system is developed by integrating various regenerative methods and plugging. Aside from the present performance dimensions such as braking torque, boost ratio and maximum conversion ratio; stopping time and energy recovery for numerous methods are analysed in diverse running conditions. It is observed that the stopping time is less for plugging and increasing in the order two, three and single switch method. Besides, energy can be recovered more in single and three switch method. Based on these performances, a new braking strategy is put forward which combine all the regenerative braking methods including plugging and switch among themselves based on the depression of brake pedal. The effectiveness of the proposed method is shown in simulation results.

Index Terms : **Electric Vehicle, Regenerative Braking , BLDC Motor**

I. INTRODUCTION

Regenerative braking is one of the technique used to increase the range of electric vehicle by charging the battery from the energy available during braking. During regenerative braking, the vehicle inertia is converted into electrical energy by using power electronic converters which makes the motor to act as the generator and send this energy back to the battery.[1,2] Regenerative braking is achieved through various methods in EVs such as:

- Utilizing a supplementary DC-DC converter for boosting the back electromotive force (back EMF) to the suitable level to charge the battery.[3-6]
- Using ultra-capacitor connected in series or in parallel to the batteries. The ultra-capacitor stores the regenerative energy surge and sends it back to the battery with the help of additional converters.[7-10]
- Using electronic gear shift technology in which the electronic gear forms multiple parallel and series connections of batteries, motor winding, and ultra-capacitor based on vehicle speed to obtain regenerative energy.[11,12]

This method needs specially designed motors with multiple windings, various battery connections, and multiple switches. Moreover, a complex switching arrangement has to be developed for execution. To overcome the disadvantages of various regenerative scheme discussed [3-12], another efficient method is proposed using the single stage converter which drives the BLDC motor. The single stage converter can perform regenerative braking by applying switching pulses in a proper sequence without any additional power converter. In this single stage converter, different types of braking methods based on different switching sequence namely single switch, two switch and three switch are studied[13,14]. In order to ensure effective braking at all speeds, various electric braking methods such as single, two, three switching topologies and plugging has to be learned.

II. SINGLE STAGE ELECTRIC BRAKING METHODS

In single stage electric braking method, the braking and energy regeneration are achieved through the single stage bidirectional DC/AC converter which is used to drive the BLDC motor. The BLDC motor driven by a single stage bidirectional converter is shown in Figure 1. R is the phase resistance and L is the phase inductance . I_a, I_b, I_c and E_a, E_b, E_c are the armature currents and back EMF respectively.S_1 to S_6 are switches and $D_1$to D_6 are the diodes and C is the DC link capacitor. A dedicated controller is used to switch the inverter in a particular sequence based on the rotor position received from hall sensors H_a, $H_b$and H_c

In single switch braking method, only one switch out of switches S_2, S_4, S_6 is operated in pulse width modulation (PWM) switching mode at each commutation state[10,15]. In two switch method, two switches out of switches S_1 to S_6 are operated in PWM switching mode at each commutation state[16,17]. In three switch method, three switches S_2, S_4, S_6 are operated in PWM switching mode at the same time in each commutation state[13,14]. The switching sequence of plugging is similar to that of two switch method, where a continuous signal is applied instead of PWM signals [18].

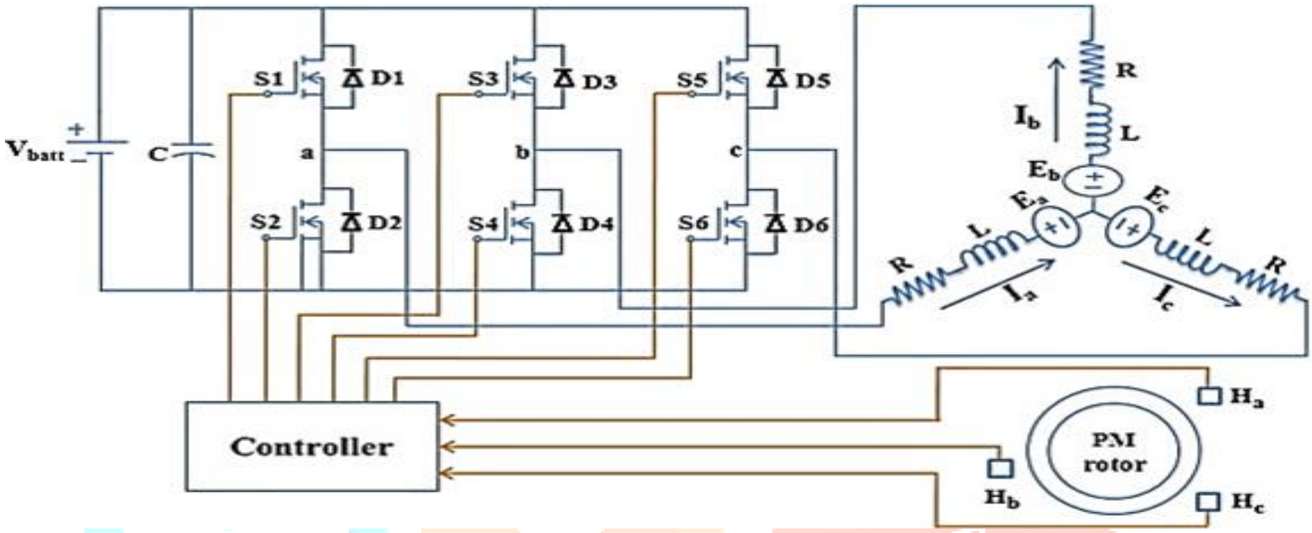

Fig 1: Equivalent circuit of BLDC motor.

III. STOPPING TIME CALCULATION

The motor dynamics is given by :

$$J\frac{d\omega}{dt} + B\omega + T_l = T_e \quad \text{....(1)}$$

Neglecting the frictional coefficient and load torque, Eq. (1) can be given as :

$$J\frac{d\omega}{dt} = T_e \quad \text{....(2)}$$

While braking, the motor torque (T_e) becomes negative and is given as :

$$T_e = -K_t i_a$$

$$J\frac{d\omega}{dt} = -K_t i_a \quad \text{....(3)}$$

The braking current of the single switch method at steady state can be given as by the equation [19] :

$$i_a = \frac{D(2V_{emf})}{R_b+2R} \quad \text{....(4)}$$

By substituting (4) in (3) and rearranging, the deceleration of single switch can be obtained as :

$$\frac{d\omega}{dt} = -\frac{K_t D(2V_{emf})}{J(R_b+2R)} \quad \text{....(5)}$$

Similarly an expression for two switch, three switch and plugging are derived and expressed in Table 1.

Where,

J = moment of inertia

ω = angular velocity

T_l = Load torque

T_e = Motor torque

K_t = Motor torque constant

i_a = Armature current

D = Duty cycle

$2V_{emf}$ = Line back-emf

R = Armature resistance per phase

R_b = Equivalent load resistance of battery comprising of internal resistance and resistance due to chemical reaction.

To see the distinct values of deceleration among the braking methods, the amount of deceleration is calculated for motor running at a specific speed, fixed battery voltage and at a certain duty cycle. The motor parameters are as in Table 2,

$R_b = 2\Omega$,$2V_{emf} = 22.5V$(corresponds to 200 rpm) , $V_{batt} = 48V$ & D =0.5

The deceleration for single switch is:

$$\frac{d\omega}{dt} = -\frac{1.0743\times0.5\times22.5}{0.1344\times(2+2\times0.17)} = -38.43\ \frac{rad}{sec^2}$$

Similarly, calculations are carried out for two switch, three switch and plugging and are presented in Table 1. It is seen that the deceleration of single switch is less and increasing in the order three, two and plugging. So the stopping time of the single switch is high and decreasing in the order three, two and plugging.

Table 1. Deceleration values of braking methods

Braking method	**Deceleration equation**	**Deceleration Value**
Single switch	$\frac{d\omega}{dt} = -\frac{K_tD(2V_{emf})}{J(R_b+2R)}$	-38.4
Three switch	$\frac{d\omega}{dt} = -\frac{K_tD(2V_{emf})}{J\left(R_b+\frac{7}{4}R\right)}$	-39.14
Two switch	$\frac{d\omega}{dt} = -\frac{K_t(2V_{emf} + DV_{batt})}{J(R_b + 2R)}$	-158.84
Plugging	$\frac{d\omega}{dt} = -\frac{K_t(2V_{emf}+V_{batt})}{J(R_b+2R)}$	-240.82

IV. PERFORMANCE EVALUATION

The performance of different braking methods is carried out using simulation. Stopping time and average energy recovery are studied from the simulation results for different speed and state of charge (SOC) of the battery. The block diagram of the performance evaluation study is shown in Fig. 2. The simulation model has a battery, three phase inverter, BLDC motor and a control module. The control module is programmed with different braking methods such as plugging, single switch, two switch and three switch. The acceleration and brake commands are provided to the control module that drives the motor for different driving conditions. When acceleration command is applied, the brake command get inactive and vice versa. The parameter used for simulation is given in table 2

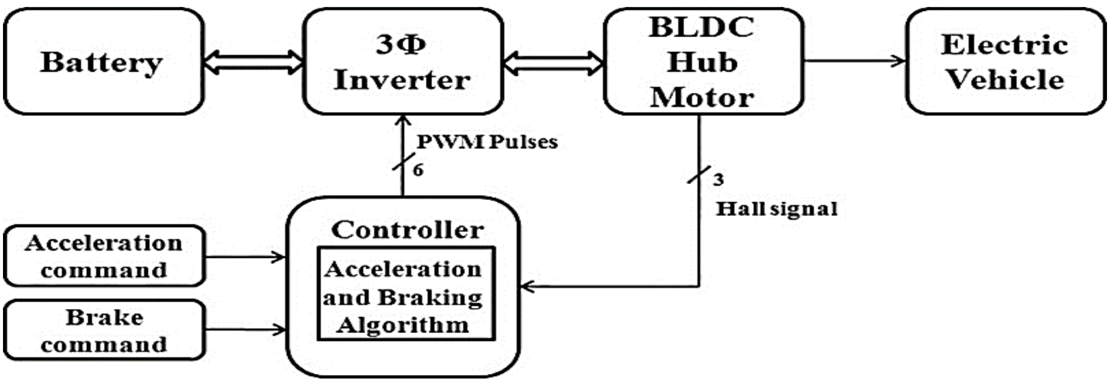

Fig 2: Block diagram for analyses of various electric braking methods.

For the performance evaluation, first the BLDC motor is allowed to run at a constant speed to apply brake signal. Each braking methods are studied for different duty cycle while maintaining battery SOC constant

V. STOPPING TIME

Fig. 3 shows the comparison of stopping time among the braking methods at various speed and SOC level. At a certain motor speed and SOC level as shown in Fig. 3(a), the stopping time is less for plugging and increasing in the order two, three and single switch. As the duty cycle increases, the stopping time of all braking methods again decreases with a higher rate. The stopping time for plugging method is constant since the duty cycle is constant. In Fig. 3(a) and 3(b), the stopping time of different switch is compared with a SOC level of 80% for the speed of 400 rpm and 200 rpm repectively. Generally, the stopping time of a motor depends on the speed at which it is running. In Fig. 3(a) and 3(b), the stopping time of motor running at 200 rpm take less time to stop compared to the motor running at the speed at 400 rpm for all the methods and the pattern followed is the same. Similarly in Fig. 3(c) and 3(d), the stopping time is compared with a SOC level of 50% and 80% for the speed of 400 rpm and 200 rpm, the same scenario can be observed.

VI. AVERAGE ENERGY RECOVERED

In Fig.4 the average energy recovered during the braking period is compared with different speed and SOC level. The average energy can be calculated as the area under the power versus time curve during the braking period. At a particular speed with a SOC level as shown in Fig. 4(a), the energy recovered by three switch is higher when compared to all the braking methods. The energy recovered is less in single switch when compared to three switch. As the duty cycle increases, the average energy recovered is gradually increases to a peak value and then decreases and finally reaches zero when duty cycle attains the value one. In plugging, there is no energy recovery also it consumes energy so it is positive. In two switch, as shown in Fig. 4(a), the average energy is negative during the duty cycle ranging from 0 to 0.5 and positive during 0.5 to 1. This is because, during the duty cycle range from 0 to 0.5, the amount of energy recovered is more compared to the amount of energy consumed from the battery over the braking period. Also as the duty cycle ranges from 0.5 to 1, the amount of energy recovered is less compared to the amount of energy consumed from the battery and it is positive. So in two switch method, effective regeneration occurs in the duty cycle range from 0 to 0.5.

Now the average energy recovery of different switch is compared to the motor running at a speed of 400 rpm and 200 rpm with 80% SOC level as shown in Fig. 4(a) and 4(b) respectively. From these figures, it is observed that the average energy recovered and average energy consumed for the speed 200 rpm is less in all the methods compared to the speed of 400 rpm. It can be clearly seen in Fig. 4(b) that the amount of energy consumed during plugging is less when the motor running at 400 rpm in Fig. 4(a). Likewise, the same is done for the motor running at 400 & 200 rpm with 50% SOC level as shown in Fig. 4(c) and 4(d) and the same results can be observed.

Table 2: Specification of BLDC motor.

Parameter	Value
Number of phases	3
Stator phase resistance (ohm)	0.17
Stator phase inductance(H)	$256e^{-6}$
Flux linkage established by magnets (V.s)	0.023354
Voltage Constant $(\boldsymbol{V_{peak\,L-L}/krpm})$	112.5
Torque constant $(\boldsymbol{Nm/A_{peak}})$	1.0743
Inertia $\boldsymbol{J}(\boldsymbol{kg.m^2})$	0.1344
Viscous damping $\boldsymbol{F}(\boldsymbol{N.ms})$	0.084
Pole pairs	23
Static friction $\boldsymbol{Tf}(\boldsymbol{N.m})$	0

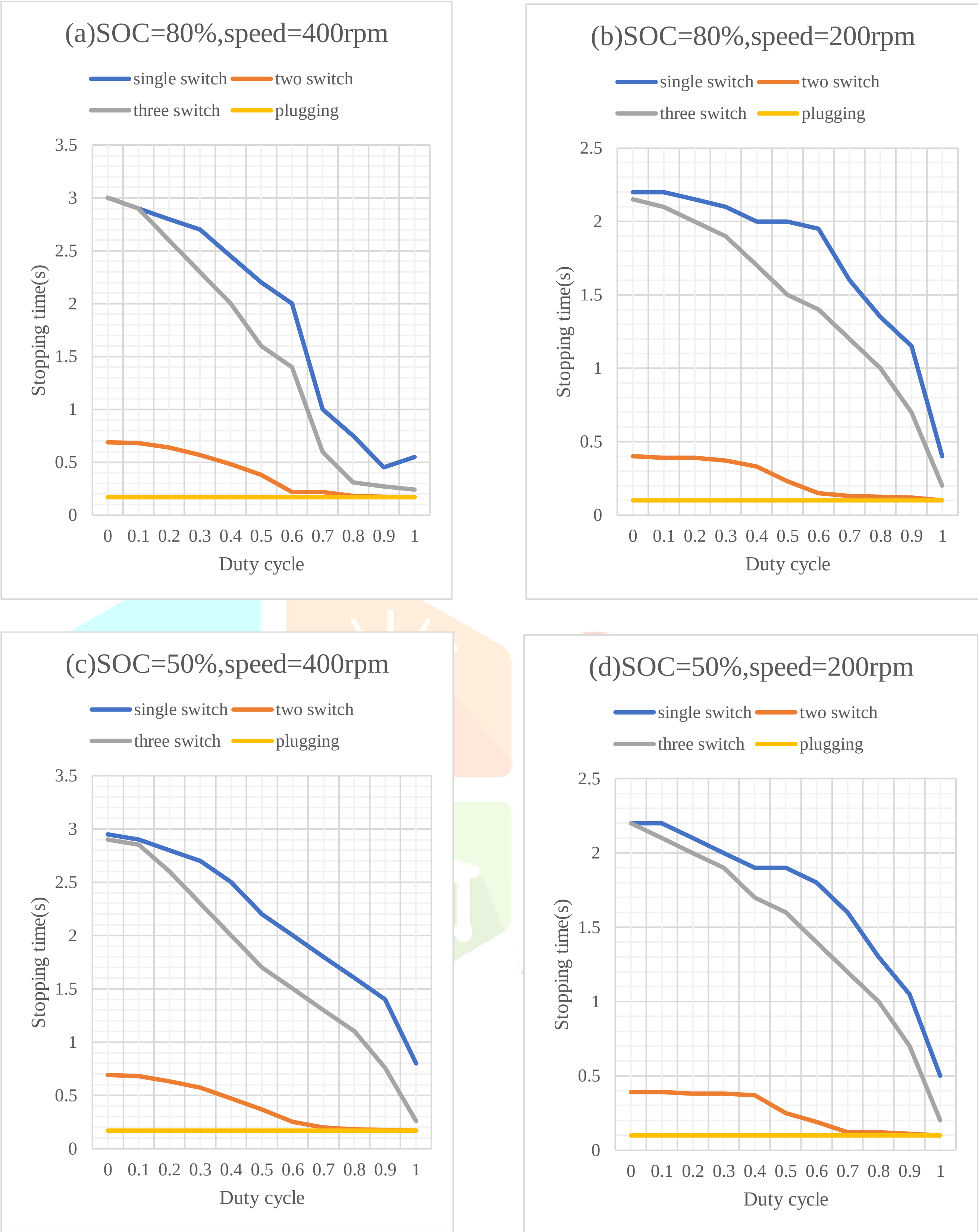

Fig 3: Simulation results for stopping time versus duty cycle for different SOC and speed

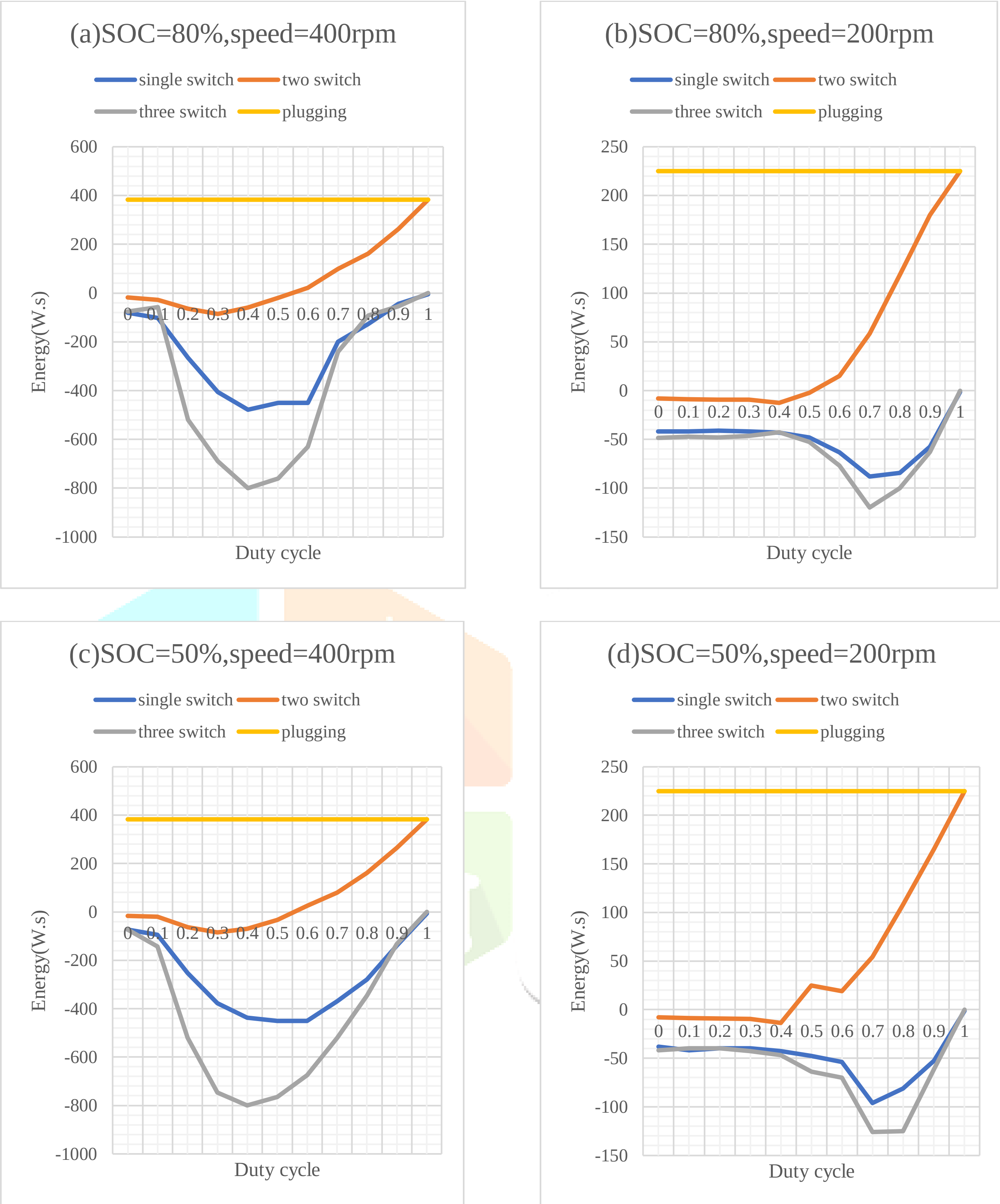

Fig 4: Simulation results for average energy recovered vs duty cycle for different SOC and speed.

VII. CONCLUSION

Different existing braking methods such as single, two, three switch topologies and plugging are combined to gain this new braking strategy. Two important parameters namely stopping time and energy regeneration are integrated to attain this proposed scheme. As a first step, their performances are studied using both numerical method and simulation. It is concluded that the regeneration is better for single, three switch method and stopping time is better for two switch and plugging.The proposed strategy is able to stop the vehicle at any speed with possible energy regeneration Simulation results are presented to show the effectiveness of the proposed method.

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