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A NOVEL SVM-DTC METHOD OF IN-WHEEL SWITCHED RELUCTANCE MOTOR CONSIDERING REGENERATIVE BRAKING CAPABILITY IN ELECTRIC VEHICLE

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Abstract- This paper investigates capability of kinetic energy regeneration during the electric vehicle (EV) speed reducing. In order to achieve this goal, an improved inverter for feeding the switched reluctance motor (SRM) as in-wheel running part of EV is proposes. A novel torque control method of SRM based on space vector modulation-direct torque control (SVM-DTC) via fuzzy logic controller (FLC) is used. By controlling speed of SRM and collecting the currents of reverse diodes from SRM windings to the battery, the state-of-charge (SOC) of the battery is enhanced. This leads to improved movement ability of EV during ECE-Driving-Cycle. The simulation results for two seconds show 0.2% enhancement of SOC when the proposed regenerative braking system is utilized. Obviously, for longer driving cycles, the amount of energy saving will be more. Hence, capability and feasibility of the proposed controlling method and regeneration system are validated.

Keywords: Direct Torque Control, Electric Vehicle, Fuzzy Logic Control, Regenerative Braking, Space Vector Modulation, Switched Reluctance Motor.

I. INTRODUCTION

Switched reluctance motor (SRM) has salient poles on both stator and rotor with concentrated winding on the stator and no winding on the rotor. As the rotor has no winding, it can tolerate high temperatures and rotate at very high speeds. The SRM achieves high torque levels at low peak currents thanks to its small air gap. The SRM drives are inherently adjustable speed drives. SRM has attracted many researchers during the recent years because of its simple construction and low manufacturing cost. Due to availability of low cost power electronic switches and fast computing controllers like digital signal processors, the conventional machines are now replaced by SRMs in some applications such as coal mining, electric vehicles, compressors, electric traction and washing machines. The main drawback of SRM is its highly non-linear torque-position characteristics and high torque ripple which in turn, causes noise and vibrations [1].

In order to minimize torque ripple of SRM, different techniques are proposed. Optimization of control parameters such as supply voltage, turn-on and turn-off angles of the switches and current levels is the most popular method. But such methods lead to overall torque reduction. In [2, 3] a novel direct torque control (DTC) technique is applied to a 3-phase 6/4 SRM where its difference between conventional DTC applied to AC machines is discussed. DTC for a 3-phase SRM is also presented in [4, 5]. In these papers, DTC method is used to control speed of a SRM in an electric vehicle (EV) and the required experiments are carried out. The main disadvantages of DTC hysteresis-based controller are: 1) variable switching frequency, 2) current and torque distortion that caused by changing sectors of voltage vector, 3) startup and low-speed operation problems etc. In order to reduce such problems, DTC control method based on space vector modulation (SVM) is presented. Because of rugged features of SRM such as non-linear characteristics, doubly-salient structure, singly-excitation, implementation of SVM on SRM is roughly tough.

Many papers described SVM method principles and applied it in conventional motors [6-10]. The braking system of EVs consists of two parts, the motor brake unit (electrical braking) and the hydraulic brake unit (mechanical braking). Regenerating of the kinetic energy which is dissipated into atmosphere in conventional braking strategies can be done in with electric motors [11, 12]. In urban driving, a significant amount of energy is consumed by braking. For instance, the regenerated kinetic energy recovered to the battery of a 1500 kg passenger car which is running at 70 km/h can supply the electric vehicle for about 1.8 km [13].

At present, efficiently recovery and the use of braking energy is extensively studied to increase the EVs efficiency. Despite the advantages of electrical braking (regenerative braking), the mechanical braking (hydraulic brake unit) is still used for several reasons. Some factors limit the regenerative braking torque, i.e. the maximum power of motor, vehicle speed, the state of charge (SOC) of battery.

When the battery is fully charged, only mechanical braking is available to stop EV. Furthermore, anti-lock braking control can be affected by excessive regenerative braking torque on the driving axle [14]. During the recent years, in order to divide mechanical and electrical braking consist of regenerative braking torque of the electric motor brake unit and the friction torque of the hydraulic brake unit, between front and rear wheels as well as dividing the demanded braking energy from driver of EV between electrical and mechanical braking, various control strategies have been developed.

A regenerative braking energy recovery control strategy for the EV using fuzzy logic control is proposed in [15] and the feasibility of this control strategy is tested with SOC and braking energy recovery. In [16], the operating principles and some braking controllers for regenerative braking to promote the efficiency of EV energy are reviewed.

In this paper, to control torque and speed of SRM as running part of EV, a novel method based on SVM-DTC via fuzzy logic control (FLC) is used. EV regeneration energy mode control is more investigated to achieve regenerative braking torque for recharging the battery during EV speed reduction. Moreover, according to proposed regeneration system, an improved inverter structure is proposed to utilize the wasted kinetic energy of electrical braking.

II. PRINCIPLES OF SVM-DTC FOR SRM

As mentioned earlier, in order to implement the DTC-SVM method on conventional machines, mathematical analysis of torque is required. Due to necessary changes in amplitude of the motor torque, required changes in the amplitude and phase of voltage vector are calculated. In the SRM, due to doubly saliency structure, single phase excitation of the stator winding and utilizing nonlinear magnetic characteristic of stator and rotor core, explicit mathematical formulation of desired changes in the motor torque and applied voltage vector is not possible. As a result, a gap is appeared in SVM-DTC of SRM in literature.

This paper fills this gap and proposes a novel torque control method by using fuzzy logic and space vector modulation. Simulation results show capability of the proposed technique to be utilized in traction application, i.e. control of speed and torque of an electric vehicle (EV) equipped by in-wheel SRM.

A. Principle of Space Vector Modulation - Direct Torque Control

The circuit most commonly used for switched reluctance drives is the asymmetric half bridge circuit. Output of each switching state is shown in Figure 1. Generally, a standard switching table with a specific switching pattern is used in the classic DTC method. That means that the possible changes in the stator flux vector and consequently the changes in electromagnetic torque are determinate because of discrete states of the inverter.

The objective of DTC-SVM scheme and its main difference with the classic DTC is estimating a reference stator voltage vector (V_S^*) and its modulating by SVM technique to drive the power electronic switches with a constant switching frequency. Thus, in every sampling time, the inverter is able to produce desired voltage vector with any direction and magnitude. Hence, the changes in stator flux could be in any direction and magnitude and consequently, the electromagnetic torque could be smoother. Thereupon, space vector modulation can be realized by the following steps:

1) Determine amplitude and phase ($\vec{V}_{ref}$, α) according to the desirable change in torque amplitude
2) Determine time durations T_a, T_b, T_0 of each voltage vector in each sector
3) Determine the switching time of each switch

In order to determine the angle (α) of desired voltage vector, a fuzzy logic controller is used that will be explained in the next section. To generate the reference voltage vector (V_{ref}) in each of the sextuplet sectors, two adjacent main voltage vectors with appropriate switching times are applied. With knowing angle α , the switching time durations can be calculated as follows:

$$\int_0^{T_z} \overline{V}_{ref}\,dt = \int_0^{T_1} \overline{V}_a\,dt + \int_{T_1}^{T_1+T_2} \overline{V}_b\,dt + \int_{T_1+T_2}^{T_z} \overline{V}_0\,dt \tag{1}$$

$$T_z \overline{V}_{ref} = \left(T_a \overline{V}_a + T_b \overline{V}_b + T_0 \overline{V}_0\right) \tag{2}$$

$$\begin{gathered} T_z \left|\overline{V}_{ref}\right| \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = \frac{2}{3} T_a V_{dc} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \\ + \frac{2}{3} T_b V_{dc} \begin{bmatrix} \cos(\pi/3) \\ \sin(\pi/3) \end{bmatrix} \\ 0 \le \alpha \le \pi/3 \end{gathered} \tag{3}$$

The switching time durations at any sextuplet sectors are:

$$\begin{aligned} T_a &= mT_z \sin\left(\frac{\pi}{3} - \alpha + \frac{n-1}{3}\pi\right) = \\ &= mT_z \sin\left(\frac{n\pi}{3} - \alpha\right) = \\ &= mT_z \left[\sin\left(\frac{n\pi}{3}\right)\cos\alpha - \cos\left(\frac{n\pi}{3}\right)\sin\alpha\right] \end{aligned} \tag{4}$$

$$\begin{aligned} T_b &= mT_z \sin\left(\alpha - \frac{n-1}{3}\pi\right) = \\ &= mT_z \left[\cos\left(\frac{(n-1)\pi}{3}\right)\sin\alpha - \sin\left(\frac{(n-1)\pi}{3}\right)\cos\alpha\right] \end{aligned} \tag{5}$$

$$T_0 = T_z - \left(T_a + T_b\right) \tag{6}$$

$$T_z = \frac{1}{f_z} \quad \text{(sampling time)} \quad \text{and} \quad m = \frac{2}{\sqrt{3}} \frac{V_{ref}}{V_{dc}} \tag{7}$$

Time duration of being ON for switches in the sector one is shown in Figure 3.

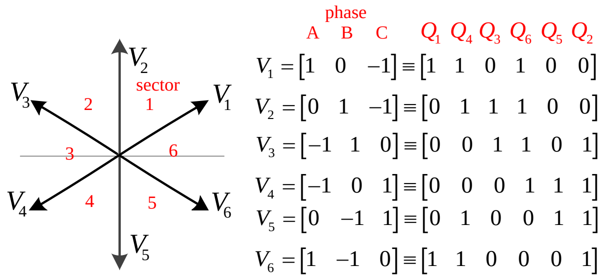


Figure 1. State of switches and related voltage vectors

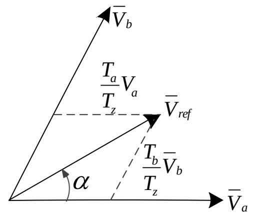


Figure 2. Adjacent main voltage vectors and reference vector

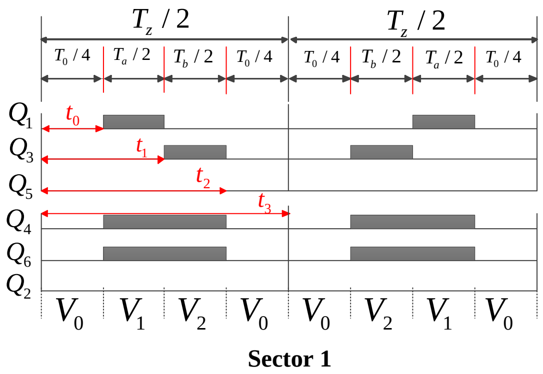
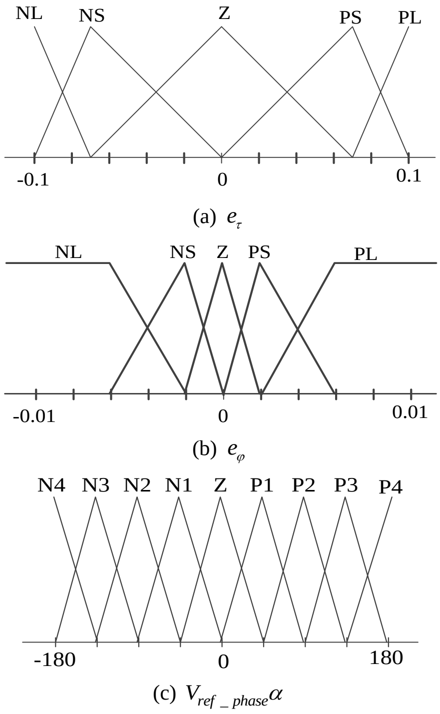


Figure 3. Space vector modulation switching patterns at sector one



(a) e_τ

(b) e_φ

(c) $V_{ref\_phase}\alpha$

Figure 4. Membership functions of fuzzy logic

Table 1. Fuzzy rules for Calculating α

e_τ / e_φ	NL	NS	Z	PS	PL
NL	N4	N3	Z	P3	P4
NS	N3	N3	Z	P3	P3
Z	N2	N2	Z	P2	P2
PS	N1	N1	Z	P1	P1
PL	N1	N1	Z	P1	P1

B. Proposed SVM-DTC-FLC for SRM

According to the descriptions in the previous section, implementation of SVM for torque control of SRM seems to be impossible. Unlike conventional DTC control method which uses two hysteresis controllers, the proposed SVM-DTC method applies fuzzy logic controller for determining the change rate of torque and flux. After calculating torque and flux error signals ($\Delta\tau=\tau^*-\tau_{act}$ and $\Delta\varphi=\varphi^*-\varphi_{act}$), the range of changes are fuzzified into several fuzzy subsets in order to select the action.

Fuzzification is carried out by using the trapezoidal membership functions. There are three membership function groups corresponding to two inputs and one outputs. Each group has a number of subsets. Inputs are the torque error ($\Delta\tau$) and the flux error ($\Delta\varphi$). Output is the phase of voltage vector (α). As seen in Figures 4 and 5, the range of torque error and flux error are defined as $-0.1\le\Delta\tau\le0.1$ and $-0.01\le\Delta\varphi\le0.01$, respectively.

After defining the range of fuzzy membership functions and subsets for $\Delta\tau$ and $\Delta\varphi$ (NL, NS, Z, PS, PL), to determine the angle of reference voltage vector, a list of fuzzy rules shown in Table 1 are used. Details of proposed controller are shown in Figure 6. At first, by using Equations (4)-(6), time duration of ON mode for switches (T_a, T_b, T_0) is determined. Then, according to sector number of the voltage vector, two adjacent main voltage vectors are known, namely $\vec{V}_a$ and $\vec{V}_b$. For instance, if the reference voltage vector is in sector one, V_a and V_b will be equal to V_1 and V_2. After using the switching Table 2 to determine turning ON time of each switch, gate commands of each of 6 switches are sent to the inverter.

III. POWER CONVERTER CONFIGURATION WITH REGENERATIVE BRAKING CAPABILITY

The circuit most commonly used for switched reluctance drives is the asymmetric half bridge circuit that its configuration, switching states and output related to each switching state can be found in [3]. In this paper, an improved structure is proposed for the inverter feeding the SRM. The connection of reverse diodes D$_1$, D$_2$ and D$_3$ is changed and they are connected together and to the battery. Thus, the magnetizing current as well as regenerative currents can be fed into the battery during electrical braking and, hence the SOC could be enhanced.

Table 2. Turning ON time for each switch

Sector	$t \le t_0$						$t_0 \le t \le t_1$						$t_1 \le t \le t_2$						$t_2 \le t \le t_3$					
	Q_1	Q_4	Q_3	Q_6	Q_5	Q_2	Q_1	Q_4	Q_3	Q_6	Q_5	Q_2	Q_1	Q_4	Q_3	Q_6	Q_5	Q_2	Q_1	Q_4	Q_3	Q_6	Q_5	Q_2
1,2,…,6	Q_{01}	Q_{02}	Q_{03}	Q_{04}	Q_{05}	Q_{06}	Q_{a1}	Q_{a2}	Q_{a3}	Q_{a4}	Q_{a5}	Q_{a6}	Q_{b1}	Q_{b2}	Q_{b3}	Q_{b4}	Q_{b5}	Q_{b6}	Q_{01}	Q_{02}	Q_{03}	Q_{04}	Q_{05}	Q_{06}

It is noteworthy that if the current feeding the ON phase is less than the required value, the phase cannot sufficiently produce torque. In addition, the torque ripple will increase. This problem is crucial when the vector control scheme is applied. The DTC benefits from higher torque production, because when the energy is returned, the commutation between phases is so performed that each phase generates the corresponding torque with the lowest current. In Figures 6 and 7, schematics of the proposed scheme are illustrated to show the principles of its operation. As shown, a boost converter is used between the battery and SRM windings to have a continuous constant voltage at the machine terminals during battery charging and discharging. Under motoring conditions, the current flows through the boost converter to the ON winding and during the demagnetization or regeneration mode, it comes back via reverse diodes to the battery to enhance its SOC.

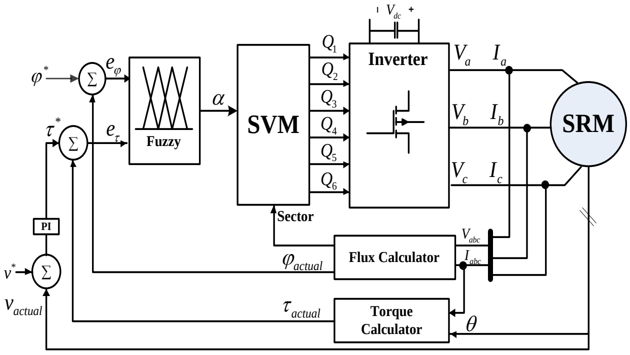


Figure 5. Structure of proposed controller for 3-phase SRM

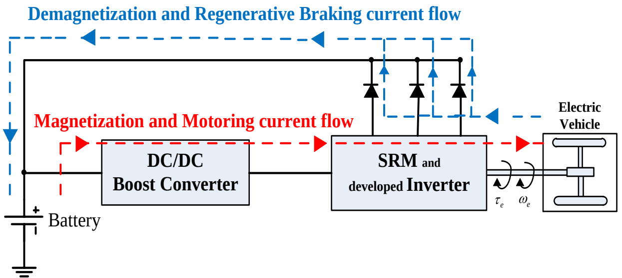


Figure 6. Conceptual schematic of the proposed structure for SRM drive for EV in motor-driving and regenerative-braking modes

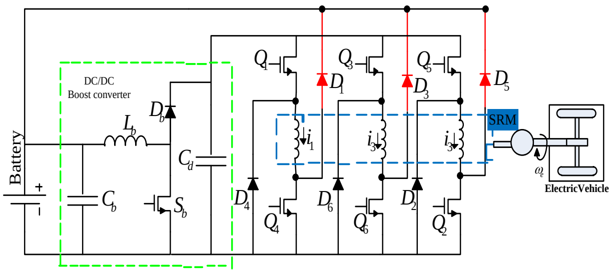


Figure 7. Configuration of proposed SRM drive

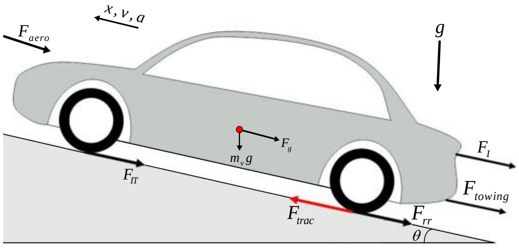


Figure 8. The forces acting on EV along a slopped road

IV. THE FORCES ACTING ON ELECTRIC VEHICLE

In this paper, in order to investigate dynamic behavior of EV, dynamic forces acting on EV, i.e. slope of road, gravity force and aerodynamic force are modeled. Such forces are applied to the SRM as an equivalent load torque. When a deceleration is required, equivalent torque is transferred from the motor to the wheels. The braking torque applied by the motor is converted to electric energy and transferred to the battery. The performance of SRM with DTC method is investigated and it is shown that proposed situation can be tracked precisely by a motor which benefits from battery recharging capability whenever electrical brake is applied and the speed of EV is decreasing. As shown in Figure 10, the vehicle is considered as a load characterized by many resistive torques [17-20]. The vehicle inertia torque is calculated by:

$$T_{inertia} = J_V \frac{d\omega_v}{dt} \tag{8}$$

A. Aerodynamic Force

During the movements of EV through the air, because of the friction of the vehicle body the aerodynamic force is generated. It is function of the frontal area shape protrusion such as side, mirrors, ducts and air passages spoilers. The aerodynamics torque is:

$$T_{aero} = \frac{1}{2} \rho A_f C_{air} R_w v^2 \tag{9}$$

B. Rolling Force

The rolling resistance is generated by the traction of tires on the road. Friction in the bearing and gearing system has the same effect. The rolling resistance is approximately constant depending on the vehicle speed and proportional to the vehicle weight. The rolling torque is:

$$T_{tire} = M \cdot g \cdot f_r \cdot R_w \tag{10}$$

C. Hill Climbing Force

The needed force to drive vehicle up a slope is simply modeled by a component of vehicle weight that acts along the slope [21]. The equivalent hill climbing torque is:

$$T_{slope} = M \cdot g \cdot \sin\theta \cdot R_w \tag{11}$$

For a given deceleration, a total torque has to be applied at wheels to track it. This demanded torque is:

$$T_{total} = T_{slope} + T_{tire} + T_{aero} T_{load} \tag{12}$$

D. Gear

The speed gear ensures transmission of the motor torque to the driving wheels. The gear is modeled by its gear ratio, transmission efficiency and inertia. The mechanical equation is given by [22]:

$$J_e \frac{d\omega}{dt} + f\,\omega_m = p\left(T_{em} - T_r\right) \tag{13}$$

where,

$$T_r = \frac{1}{\eta N_{red}} T_v \tag{14}$$

$$J_e = J + \frac{J_v}{\eta N_{red}^2} \tag{15}$$

V. SIMULATION AND RESULTS

In this section, effectiveness of the proposed control method and regenerative energy systems are validated. First, to examine capability of SVM-DTC-FLC method, step changes in the reference value of SRM torque is applied. Figure 9 shows tracking of reference torque and actual and reference torque with SVM-DTC method. Low torque ripple amplitude and fast dynamic response are the most important features as result. Having these features of controller is necessary for utilizing as EV running part.

As mentioned earlier, the requirements of EV modeling, such as weight, friction and aerodynamic forces, are modeled as a load torque to evaluate capability of the SRM as an in-wheel EV driver. The road slope should be taken into account to investigate the capability of energy recovery (regenerative breaker). When an EV is in a slide position, electric braking could lead to absorption of kinetic energy of wheels.

In the simulations, it is shown that the reference torque and hence, the reference speed can be tracked satisfactorily. It is noteworthy that driving time of standard cycles is usually between 600-2000 seconds. Due to hardware limitations, simulation for such period is not possible and hence, the simulation time is reduced to 2 seconds. Despite the short time of simulation, the trajectory driving cycle is similar to actual one to show the capability of SRM control system.

In this paper, standard ECE-driving-cycle is selected as speed reference for the control system. The reference and actual curves of EV speed is illustrated in Figure 10, where a low difference is observed between them. In addition, the reference and actual torque is shown in Figure 11. As observed, the maximum torque required to achieve the driving cycle is equal to 8 Nm. As mentioned before, Diodes D1, D3 and D5 conduct the regeneration current form the motor windings to the battery. Figure 12 shows the current of D1. As evident, average of this current is positive which means enhanced SOC for the battery. Regarding the driving cycle of EV, during the periods 0.2-0.4 s, 0.8-1 s, 1.5-1.7 s and 1.7-1.9 s, the speed is decreasing and hence, electric braking is needed.

Thereupon, it can be expected that during such periods, the kinetic energy of EV could be returned to the battery. Figure 13 shows the battery SOC. In the period 0.2-0.4 s, the EV speed and its variation are low and hence, the regeneration energy cannot be noticeable and just, the negative slope of SOC is reduced. But, in the remaining periods of speed reduction, in particular during 1.6-1.9 s, where a significant speed variation is observed, the SOC experiences significant enhancement. In order to evaluate influence of the proposed regenerative braking system, the battery SOC is shown with and without recovery diodes in Figure 14. As observed, the SOC is enhanced up to 0.2% in the simulation period, which clearly verifies the effectiveness of proposed regenerative energy system for supplying the energy during longer driving cycles.

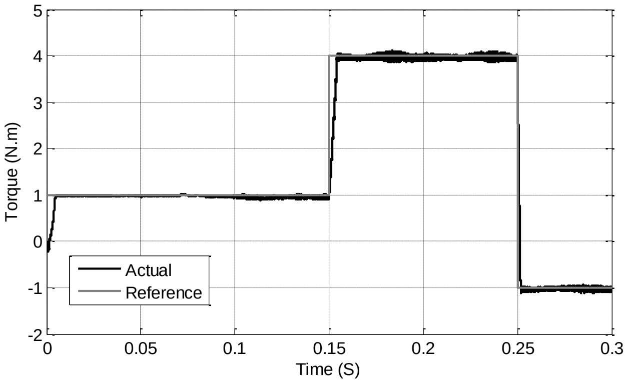


Figure 9. Torque tracking with SVM-DTC method

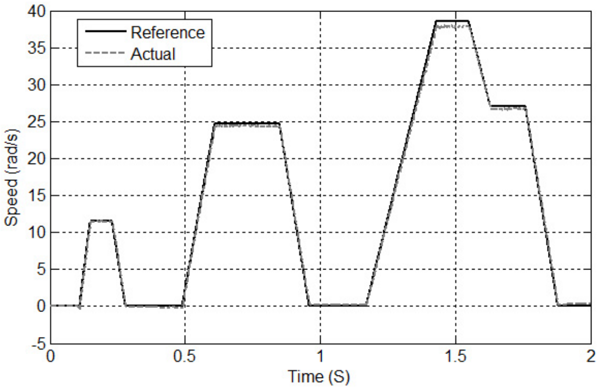


Figure 10. ECE-Driving-Cycle speed tracking

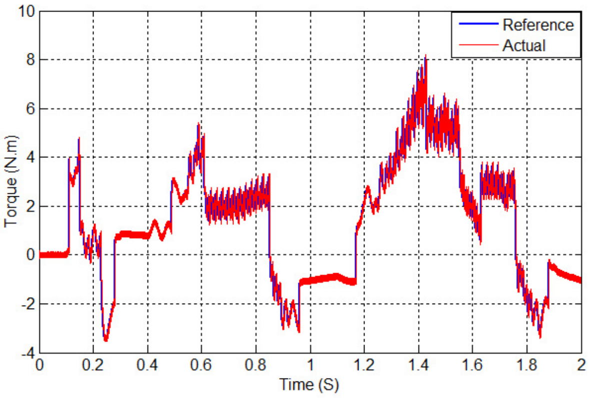


Figure 11. Demanded torque and actual torque of SRM in tracking of ECE-Driving-Cycle

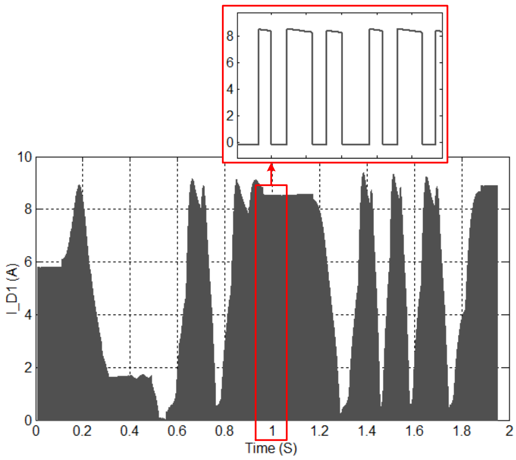


Figure 12. Current of reverse diode (ID_1)

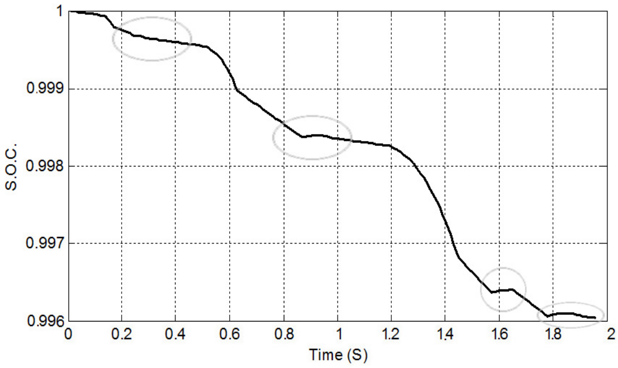


Figure 13. SOC for battery in regenerative braking mode

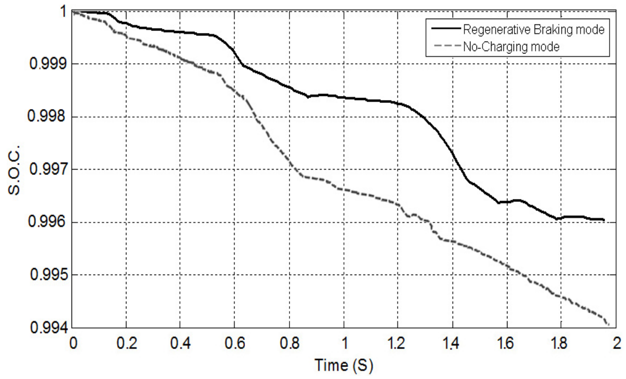


Figure 14. SOC for battery with and without regenerative braking system during ECE drive cycle

VI. CONCLUSION

In this paper, a novel, effective and simple approach based on SVM-DTC-FLC is proposed to control the speed of SRM and restore the electrical braking energy to the battery. To achieve this goal, a new improved structure for the inverter feeding the SRM is suggested. The forces acting on EV, including the road slope is modeled by an equivalent force. The standard ECE driving cycle is considered for simulation. The simulation results show that the proposed control system and modified inverter lead to satisfactorily tracking the rotor speed with high precision and low torque ripple. Since the battery is used in EVs to feed the motor, its SOC is decreased during driving.

The modified inverter controlled by SVM-DTC returns the kinetic energy to the battery during electrical braking and hence, increases its SOC. The simulation for 2 seconds shows 0.2% enhancement in SOC when the regenerative braking system is utilized. Obviously, for longer driving cycles, the amount of energy saving will be more.

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