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Transient and Steady States Analysis of Traction Motor Drive with Regenerative Braking and Using Modified Direct Torque Control (SVM-DTC)

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Abstract: Direct torque control (DTC) is a suitable control method for electric drives which are supplied by inverters, specially voltage source inverters (VSI). This method has some advantages compared with other methods such as field oriented control (FOC) with some drawbacks like switching frequency variation, that leads to introduce DTC improvement methods. Using space vector modulator (SVM) in DTC structure is the most important method that is referred to as space vector modulator for direct torque control (SVM-DTC). Utilizing regenerative braking method in electrical transportation makes it necessary to analyze the traction motor behavior in regenerative braking mode. In this paper three major types of SVM-DTC are mentioned and SVM-DTC method with Closed- Loop Torque and Flux Control in the Stator flux coordinates is used for simulation of traction motor driver of GhatarShahri Esfahan Organization. Moreover, traction motor behavior in regenerative braking mode using SVM-DTC driver is simulated. The simulation results are analyzed in the paper.

Keywords: Direct Torque Control (DTC); Space Vector Modulation (SVM); Traction Motor Drive; Speed Control of Induction Motors; Regenerative Braking.

I. INTRODUCTION

Urban transportation is one of the most important consumer of energy and an emission source of greenhouse gases. Utilizing induction motors with high performance and less maintenance have resulted in growth of using this drive in the electric transportation industry. Deployment of induction motor in transportation applications requires a driving method with fast response, high reliability and simple implementation approach [1]. Different control methods including direct torque control (DTC), field oriented control (FOC), scalar control and volt per hertz (V/Hz) control methods have been proposed to control inverter fed induction motors. Nowadays, FOC and DTC methods are more utilizable than the other methods.

If the magnetic flux and torque could be controlled indirectly using stator current components, there is no reason that the magnetic flux and torque could not be controlled directly without using interface current control loops.

This issue is the difference between DTC and FOC i.e. FOC uses an indirect method of torque control. Using direct torque controlmethod leads to faster response to torque vanatlon in DTC compared with FOe. Therefore, DTC is more suitable for transportation applications i.e. induction traction motor drives [2-5]. Creating a suitable condition for energy recovery during speed reduction in braking is one of the most important concerns in operation of the electric transportation systems. Electric brakes are implemented in different methods, such as plugging, dynamic braking and regenerative braking [6].

This paper discusses transient and steady states analysis of induction traction motor, considering energy recovery in regenerative braking. Moreover, the performance of space vector modulation based direct torque control (SVM-DTC) method is analyzed and simulated using MA TLAB/Simulink, in order to control and drive of induction traction motor.

A. Induction traction motor characteristics

One of the most important features of a traction motor is its lower weight and dimension compared with conventional motors. The other difference is its special design to tolerate long term overloads. Favorable characteristics of electric traction motor are:

High density of torque and power

Vast constant power operation region

High efficiency

Minimum number of sensors

Maximum torque of three phase induction motor is as follows:

$$T_p = \frac{3P}{\omega_s} V_s^2 \frac{R_r / S}{(R_r / S)^2 + (\omega_s L_r)^2}$$

The motor dynamic torque equation is:

$$T_m - T_e = -J(d\omega / dt)$$

Where J is the moment of the inertia and w is the rotor speed.

The torque-speed characteristic of induction motor is shown in Fig. 1. The torque-speed characteristic contains generating, motoring and braking mode of operation.

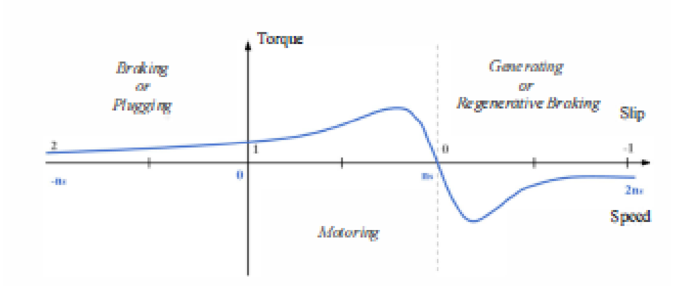

Fig.1 Torque speed Characteristics of induction motor

Traction motor operates in generating mode during braking or speed reduction, if the stator flux vector lags behind the rotor flux vector. Considering this issue, traction motor should not be separated from the inverter during energy regeneration; because this results in loss of stator flux vector and hence the linkage flux decreases to zero rapidly. Therefore, an appropriate driver should be provided in which by applying a suitable switching pattern, the stator flux vector locates in a suitable position related to the rotor flux vector. Thus, an appropriate negative electromagnetic torque is produced for energy regeneration. With regard to (2), speed increases and decreases when the difference between mechanical and electromagnetic torque is less and more than zero, respectively.

B. DTC Method

DTC method provides suitable switching pattern for VSI through two control loops of stator flux and electromagnetic torque. It is necessary to estimate these quantities to form the control loops. Nevertheless, the differences between estimated and reference values are utilized in a different way compared with FOe. DTC does not need current controllers and uses two and three level hysteresis comparators to control flux and torque, respectively. Fig. 2 shows the block diagram of DTe. The hysteresis controllers determine the flux and torque variation with considering that the flux and torque error is out of specified limits or not. Look-up table is another part of DTC structure. Inputs of look-up table are: flux and torque hysteresis controllers output and the specific sector in which flux vector is rotating. Consequently, an appropriate voltage vector based on the switching strategy is produced [7].

II. MODIFIED DIRECT TORQUE CONTROL

In modified DTC, to adjust switching frequency at a fixed value and take advantages of SVM, hysteresis controllers and look-up table are replaced by SVM. This modulation method has advantages such as fixed switching frequency, decreasing power loss and torque ripple, softer starting and lower sampling frequency in comparison with the method uses hysteresis controllers and look-up table [8-9].

There are several methods which implement SVM-DTC. Three main methods i.e. closed loop torque control, closed loop flux and torque control in polar coordinates and closed loop flux and torque control in the stator flux coordinates are studied. These schemes use flux and/or torque feedback and pass their error relative to reference values through appropriate controllers to generate reference voltage vector as SVM block input [9-10].

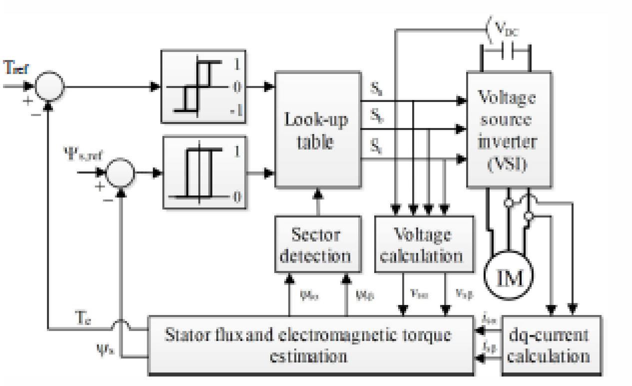

Fig. 2. Block diagram of DTe.

A. SVM-DTC based on closed loop torque control

Block diagram of SVM-DTC based on closed loop torque control is shown in Fig. 3. This scheme is designed based on the following equation.

$$\vec{v}_s = \frac{\Delta\vec{\psi}_s}{\Delta t} + R_s i_s$$

In order to use SVM, stator reference voltage vector should be generated by means of the controllers before modulator. Magnitude and angle of the voltage vector depends on the difference between estimated and reference values. If the error of stator voltage and flux vector could be estimated, the reference voltage vector is generated by (3). Fig. 4 shows the flux vectors in vector space. Referring to Fig. 4, the reference flux can be calculated as:

$$\vec{\psi}_{sc} = |\psi_{sc}| e^{(\hat{\gamma}_{ss} + \Delta\delta_{\psi})}$$

Where $_{Ilf/}S_{cl}$ is reference flux and LlOIf/ is output of PI controller.

B. SVM-DTC based on closed loop flux and torque control in polar coordinates

In the previous method, torque is controlled in closed loop, but there is no control on flux and hence it is processed in open loop. Therefore, SVM-DTC based on closed loop flux and torque control in polar coordinates was introduced. In this method the flux is controlled in a closed loop structure, as it is shown in Fig. 5.

C. SVM-DTC based on closed loop flux and torque control in stator flux coordinates

Two previous described schemes are designed based on (3), in other words, a type of differentiator has been used in their structures. Therefore, these schemes are too sensitive to disturbances and are more susceptible to instability in case of fault occurrence in control loop. These problems lead to propose SVM-DTC based on closed loop flux and torque control in stator flux coordinates. Block diagram of this scheme is shown in Fig. 6. This scheme uses two PI controllers and a coordination transformation block. This method does not have the problems of previous methods and is more appropriate for industrial applications, but it is a little complicated in

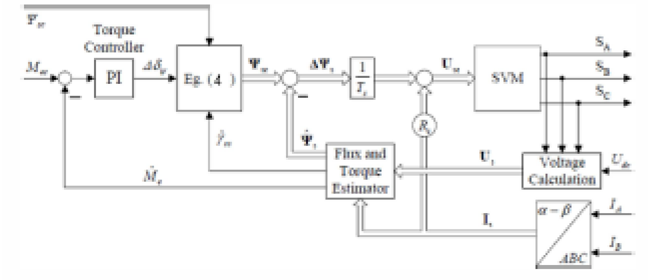

Fig. 3.Block diagram of SVM-DTC based on closed loop torque control [9]

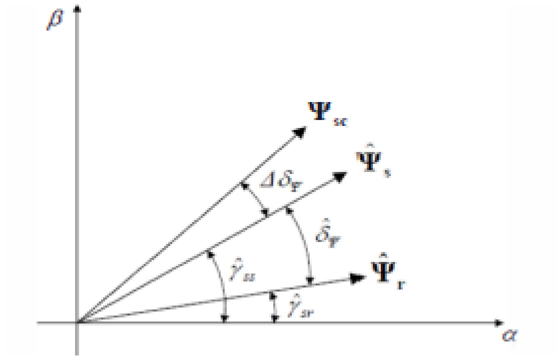

Fig. 4. Flux vectors.

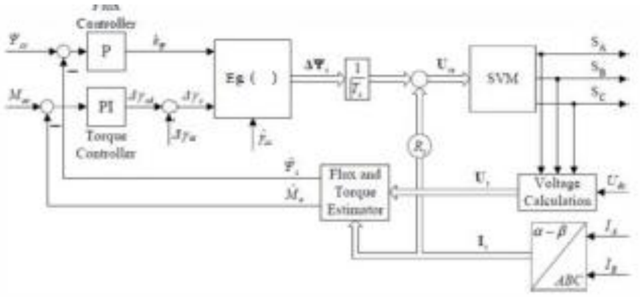

Fig. 5.Block diagram of SVM-DTC based on closed loop flux and Torque control in polar coordinates [9].

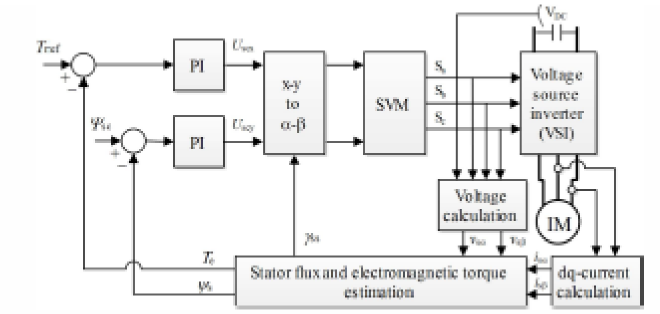

Fig. 6.Block diagram of SVM-DTC based on closed loop flux Torque control in stator flux coordinates.

structure compared with the previous methods. Reference voltage vector is generated by means of PI controllers output and the angle of stator flux vector.

III. REGENERATION THROUGH TRACTION MOTOR

DECELERATION

As it is mentioned before, traction motor speed reduces when electromagnetic torque is less than mechanical torque. Therefore using SVM-DTC method, it is possible to control motor speed in the best way by means of electromagnetic torque variation. This has resulted in introduction of regenerative braking as one of the important methods for control of traction motor speed

If the bilateral inverter is used in motor drive, it is possible to regenerate machine energy. If there is no path for current flow, the regenerated energy increases voltage of DC link. A straightforward approach to this problem is to waste the energy in dynamic resistor which is in parallel with the DC link. This approach is known as dynamic braking. In addition to energy loss, dynamic braking has negative impacts on the ventilation and longevity of equipments; however, it has fast dynamic and provides suitable controllability.

Transferring the energy to traction substation is another method which is used in metro [11]. The main equipment in this method is an inverter. Therefore, it is relatively simple and inexpensive method. However, power quality problems make it necessary to use power quality improvement equipments such as active and passive filters.

The third method for using regenerated energy is to store energy in storage devices such as flywheel and super-capacitor. These equipments has attracted researchers with having long Lifetime and high rate of charge and discharge [12 -13].

Some designers believe that it is possible to transfer the energy to the other trains. However, it should be noticed that this approach could not be feasible and profitable solely; because, only it is possible to use regenerated energy while other trains are in generating mode. Furthermore, the rate of energy use is not controllable. In this condition, it is necessary utilizing dynamic braking or transferring the energy to traction substation. In addition, it is possible that trains have negative impacts on DC link voltage while the growth of interaction between trains excites the oscillation modes of traction system and hence traction system may be deviated from the appropriate conditions. Therefore, it is proposed to use the dynamic braking alongside the energy storage. This leads to take advantages of the both methods. Moreover, through this approach the oscillations can be damped. Because, the energy of positive oscillations will be dissipated in dynamic resistance and negative oscillations will be compensated by means of energy storage devices such as super-capacitor.

It is proposed to use energy storages in normal voltage range while the dynamic braking operates in overvoltage condition which usually occurs in speed reduction.

IV. SIMULATION RESULTS

Matlab/Simulink models are used for simulation studies. Adjustments related to PI controller and its details are in accordance with [9]. In following section, the SVM-DTC is simulated in motor start-up and constant speed modes. Thereafter, the performance of SVM-DTC and traction motor in regenerative braking is simulated and analyzed. In order to simulate motor operation in regenerative mode, characteristics of the traction motor, Inverter and train are taken from GhatarShahri Esfahan Organization documents [14]. The parameters of Traction motor, inverter and train are shown in Table I.

A. Start-up and load exerting

As mentioned in section III, SVM-DTC based on closed loop flux and torque control in stator flux coordinates, is suitable for industrial applications; hence this scheme is used in the simulation. Simulation block diagram of this scheme is shown in Fig. 7. The simulation of this section demonstrates the performance of SVM-DTC in start-up and load exerting beside its effects on the behavior of the motor.

The simulation is implemented in discrete state with processing frequency of 100 kHz. The frequency of SVM is 5kHz. AtfIrst, simulation is implemented based on reference speed of 201.4 rad/s, maximum reference torque of 1224.3N.m, reference flux of 2.08 Wh and with a load torque characteristic given in Fig. 8. Simulation results are shown in Fig. 9. In this part, to simplify and save time, the load torque is set as constant value (the load inertia was omitted) and motor start-up is simulated in no-load condition. Then the mechanical load is exerted. Through this approach, the behavior of traction motor and driver could be illustrated better.

After load exerting, speed and torque control is diffIcult. Soft and small increase in electromagnetic torque at time of load exerting is towards speed control so that speed drop could be compensated. However, because of increasing stator flux frequency to its nominal value, SVM-DTC cannot increase electromagnetic torque with an appropriate dynamic. Consequently, controller could not supply mechanical load torque and compensate speed drop effIciently, even if reference torque is at maximum value.

If reference speed decreases, stator flux frequency will also decrease into a value less than nominal frequency. Therefore, even at the presence of high load torque, SVM-DTC controls speed and torque without any problem in dynamic of the controller. To confIrm this issue, simulation is repeated with reference speed of 170 rad/s, maximum reference torque of 1224.3 N.m, reference flux of 2.08 Wh. Load torque characteristic is given in Fig. 10.

Simulation results are shown in Fig. 11. As it was predictable, using the new values SVM-DTC operation has been improved compared with the previous simulation. Torque and flux ripple have been reduced; moreover, torque and speed controllability has been enhanced with an acceptable dynamic.

After applying load, stator current rises to supply adequate torque and power where speed drops. However, speed drop is not so considerable and it is adjusted to the reference speed after a short time.

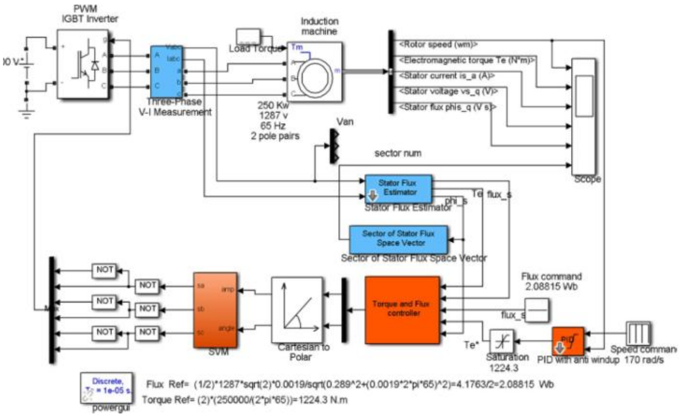

Fig. 7. Block diagram of SYM-DTC based on closed loop flux and torque control in stator flux coordinates.

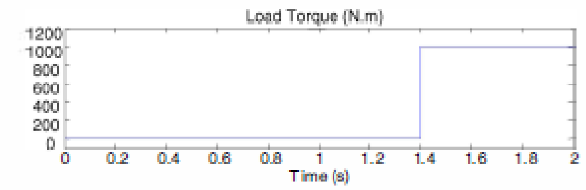

Fig. 10. Applied load torque at speed of 170 rad/s.

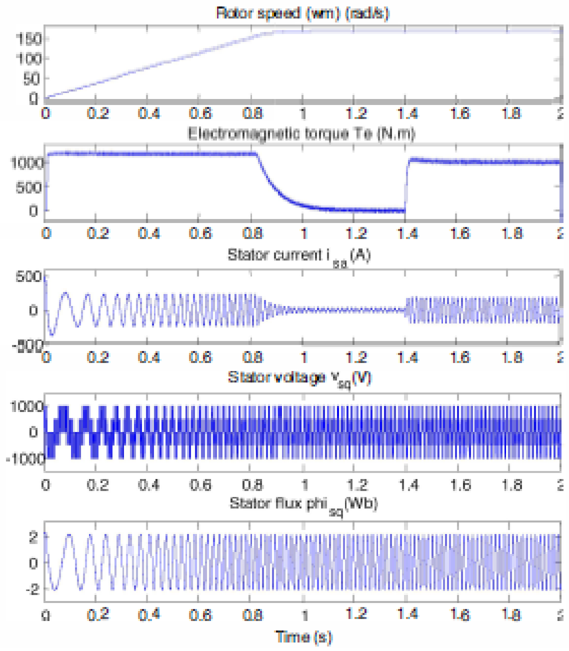

Fig. 8. Simulation results of SVM-DTC with reference speed of 201.4 rad/s

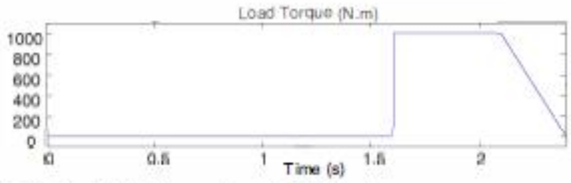

Fig. 8. Applied load torque at speed of 201.4 rad/s.

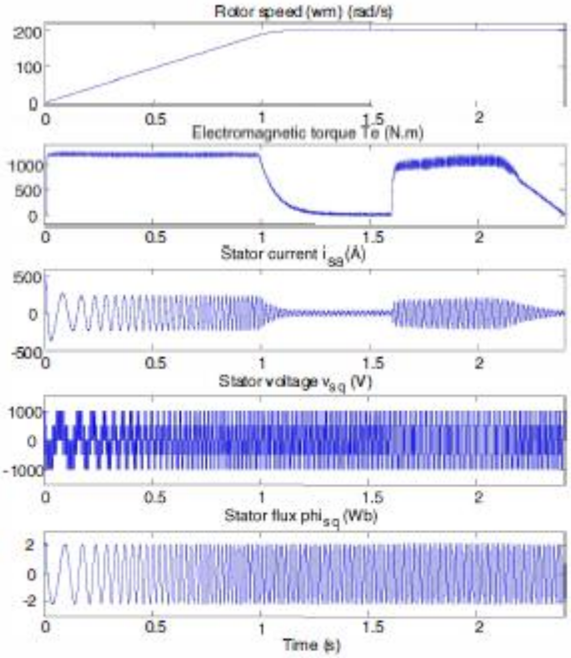

Fig. 9.Simulation results of SVM-DTC with reference speed of 170 rad/s

B. Regenerative Braking

In this section, traction motor operation in generating mode and its effects on traction system is simulated. Fig. 12 represents block diagram of a traction system for a power car which includes 4 traction motors. Each motor responds to 1112 of total mechanical load.In the regenerative braking, the speed reference could beset to any value less than actual rotor speed; however, forreaching more deceleration, the reference value in regenerativebraking is set to zero. Due to very smooth performance of thecontroller near the reference value (zero), it is recommended toset torque reference to maximum negative value with desirabledecrease rate or utilizing mechanical brakes in this range;although, using mechanical brakes is inevitable for Emergencybraking.Fig. 13 shows the DC-link voltage variations duringregenerative braking with and without regenerated energyabsorption. As it is seen, DC link voltage has a great differencewith its nominal value, if there is no path for current to flowbetween traction substation and motors. In this situation, the

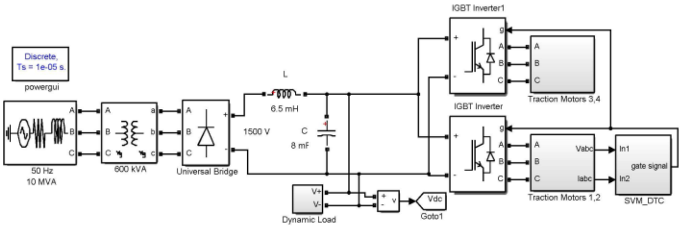

Fig. 10. Block diagram of the regenerative braking simulation

regenerated current flows through DC-link capacitor with high rate; accordingly, DC-link voltage increases.

Regenerated energy can be absorbed by one of the methods mentioned in section IV. A braking chopper is designed for thispurpose. This chopper connects the load (which can be energystorage device, dynamic resistor or traction substation) inparallel with the DC link capacitor after crossing DC link
voltage from a specified value (in this case IS00V). As it is represented in Figs. 10, 11, DC link voltage is regulated by means of energy absorption methods.

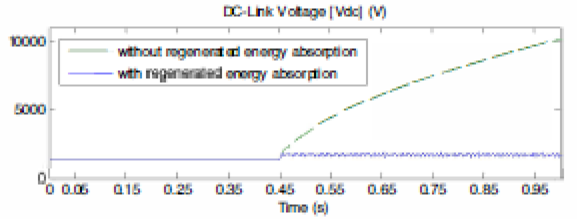

Fig. 13. DC-link behavior during regenerative braking with and without regenerated energy absorption.

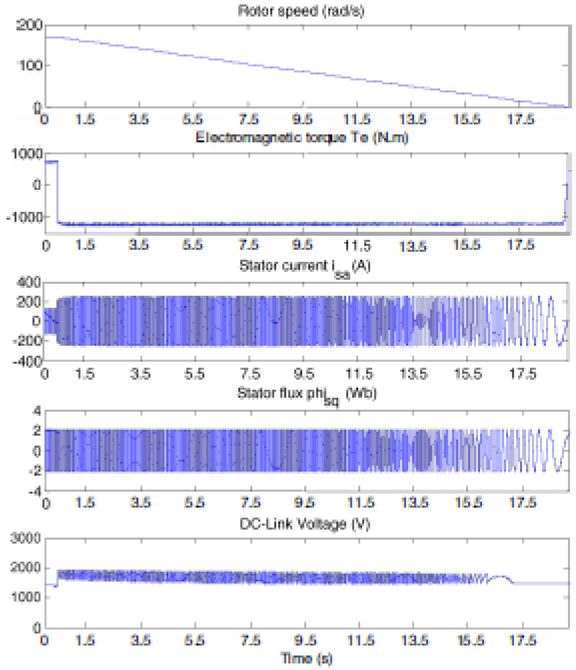

Fig :11 Traction motor and DC-link behavior during regenerative brakingwith regenerated energy absorption.

Fig. 11 shows the behavior of the motor during regenerative braking. The results demonstrate the performance of SVM-DTC drive with high quality for regenerative braking. Traction motors simply could work in regenerative braking (generation mode) using SVM-DTC by setting lower speed than current motor speed as reference value. Consequently, the reference torque would be negative. Adjustment of the speed reduction rate can be implemented through change in lower limit of electromagnetic torque limiters.

V. CONCLUSION

In the case of induction traction motor control methods, DTC has better performance. DTC has some shortcoming such as varying switching frequency proportional to motor speed variation. Therefore, it is necessary to use maximum sampling frequency in DTC. These issues result in increasing flux ripple in lower speed and increasing torque ripple in higher speed inaddition to increasing switching loss. SVM-DTC with fixed switching frequency solves these problems significantly.

Among different methods of electrical braking, regenerative braking has special advantages such as reduction in energy consumption and improvement in power quality of DC link. SVM-DTC operation is also appropriate and acceptable in regenerative braking. Therefore, it is suggested to utilize SVM-DTC in electric rail transportation applications.

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