Regenerative Braking and Torque Ripple Reduction of Induction Motor Drives Based on Space Vector Modulation Direct Torque Control Strategy

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ABSTRACT:The induction motorsare the most used one in electrical drives. For the electrical drives with frequent starting, stopping or reversing regimes the consumed electrical energy is important and the overall efficiency of the system decreases significantly. Nowadays the worldwide manufactures in the power converters production area proposed as an alternative solution the regenerative electrical drives. This paper embarks on the issues of bidirectional power conversion, regenerative braking and energy storage. A simplified and cost effective method of three phase inverter fed induction motor drive capable of regenerative energy storage is discussed. This method is very useful for Hybrid Electric Vehicles, Traction Drive and hoist drive applications. The proposed method is focused on smooth control and energy efficiency of AC drive systems. A simulation model has been developed for the analysis of system dynamics and power flow. The classical direct torque control (CDTC) strategy provides the faster dynamic response.There are some disadvantages of classical direct torque control strategy such asit is associated with large torque ripple. Space vector modulation DTC strategy is proposed for reducing torque ripple of induction motor drives.

KEYWORDS: Direct Torque Control, Space Vector Modulation, Induction Motor, Regenerative Braking, Inverter.

I.INTRODUCTION

Motion control is required in large number of industrial and domestic applications like transportation systems, rolling mills, paper machines, textile mills, machine tools, fans, pumps, robots, washing machines etc. Systems employed for motion control are called drives, and may employ any of prime movers such as diesel or petrol engines, gas or steam turbines, steam engines, hydraulic motors and electric motors, for supplying mechanical energy for motion control. Drives employing electric motors are known as electrical drives. An electric drive can be defined as an electromechanical device for converting electrical energy into mechanical energy to impart motion to different machines and mechanisms for various kinds of process control [1].The electromagnetic forces or torques developed in the driving motor tend to propagate motion of the drive system. This motion may be uniform if the linear velocity (in the case of translational motion) or the angular velocity (in the case of rotational motion) is constant, or non-uniform, as it occurs while starting, braking or changing the load on the drive. In case of uniform motion the torque developed by the driving motor is to overcome any resisting torque offered by the driven equipment as well as the torque due to friction. In other words, only static resisting torques, commonly called as load torques, are to be counterbalanced, if the motion were uniform [2].

In recent years induction motor control techniques have been the field of interest of many researchers to find out different solutions for induction motor control having the features of precise and quick torque response, and reduction of the complexity of field oriented control. The classical direct torque control (CDTC) technique has been recognized as the simple and viable solution to achieve this requirements [3]. CDTC is one of the most excellent and efficient control strategies of induction motor. This technique is based on decoupled control of torque and stator flux and today it is one of the most actively researched control techniques where the aim is to control effectively the torque and flux.In

this paper, A most efficient braking named as regenerative braking is explained for induction motor drives. Torque ripple is reduced with help of space vector modulation strategy [4].

II. REGENERATIVE BRAKING OF INDUCTION MOTOR DRIVES

We know the power input to an induction motor is given by:

$$P_{in} = 3VI_s \cos \phi_s \quad (1)$$

Where:
V = Stator Phase Voltage I_s= Stator Phase Current
ϕ_s = Phase Angle between Phase Voltage and Phase Current

For motoring operation $\phi_s< 90°$ and for braking operation $\phi_s> 90°$. When the speed of the motor is more than the synchronous speed, relative speed between the motor conductors and air gap rotating field reverses, as a result the phase angle because greater than 90° and the power flow reverse and thus regenerative braking takes place. The nature of the speed torque curves are shown in the figure below.
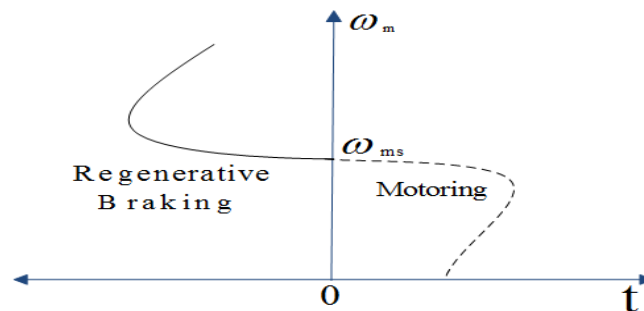

Fig. 1Regenerative Braking of Induction Motor Drives

If the source frequency is fixed then the regenerative braking ofinduction motor can only take place if the speed of the motor is greater than synchronous speed, but with a variable frequency source regenerative braking of induction motor can occur for speeds lower than synchronousspeed. The main advantage of this kind of braking can be said that the generated power is use fully employed and the maindisadvantage of this type ofbraking is that for fixed frequency sources, braking cannot happen below synchronous speeds [5].

III. CLASSICAL DIRECT TORQUE CONTROL STRATEGY

The classical direct torque control strategyis a closed loop control scheme, the important elements of the control structure being: the power supply circuit, a three phase voltage source inverter, the induction motor, the speed controller to generate the torque command and the DTC controller. The CDTC controller again consists of torque and flux estimation block, two hysteresis controllers and sector selection block, the output of the CDTC controller is the gating pulses for the inverter.

The CDTC strategy does not require coordinate transformation as all the control procedures are carried out in stationary frame of reference. So this scheme does not suffer from parameter variations to the extent that other control techniques do. Also there is no feedback current control loop due to which the control actions do not suffer from the delays inherent in the current controllers, no pulse width modulator, no PI controllers, and no rotor speed or position sensor. So it is a sensorless control technique which operates the motor without requiring a shaft mounted mechanical sensor. Here on-line torque and flux estimators are used for closing the loop [6]. Here the torque and stator flux are controlled directly by using hysteresis comparators. Fig.2 shows the basic block diagram of classical DTC strategy.The basic principle of DTC is to directly select stator voltage vectors according to the torque and flux errors which are the differences between the references of torque and stator flux linkage and their actual values. The governing equation for torque for this scheme is due to the interaction of stator and rotor fields. Torque and stator flux linkage are computed

from measured motor terminal quantities i.e. stator voltages and current [7]-[9]. An optimal voltage vector for the switching of VSI is selected among the six non-zero voltage vectors and two zero voltage vectors by the hysteresis control of stator flux and torque.
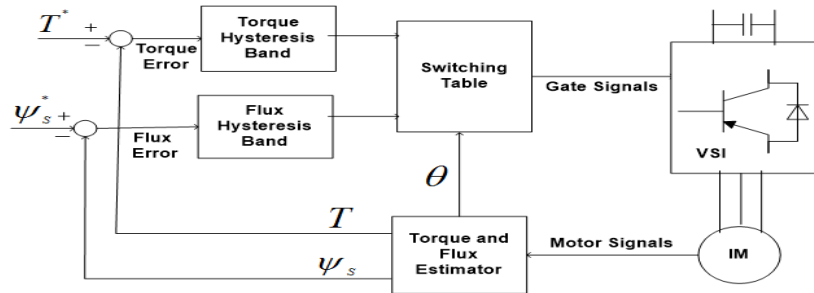

Fig. 2 Block diagram of classical DTC strategy for IM drives

A. TORQUE AND FLUX CALCULATION

This is the simplest method of stator flux estimation, where the machine terminal voltages and currents are sensed and from the stationary frame equivalent circuit the fluxes are computed.

The estimated stator flux is given by the following equations:

$$V_{sd} = V_a \, and \qquad V_{sq} = -\frac{1}{\sqrt{3}}(V_a + 2V_b)\,(2)$$

$$I_{sd} = I_a \quad and \qquad I_{sq} = -\frac{1}{\sqrt{3}}(I_a + 2I_b)\,(3)$$

$$\Psi_{sd} = \int(V_{sd} - I_{sd}R_s)\,(4)$$

$$\Psi_{sq} = \int(V_{sq} - I_{sq}R_s)\,(5)$$

The magnitude of stator flux is given by:

$$\Psi_s = \sqrt{(\Psi_{sd}{}^2 + (\Psi_{sq}{}^2)}\,(6)$$

Torque is calculated as per below relation:

$$T_e = \frac{3}{2}\frac{P}{2}(\Psi_{sd}I_{sq} - \Psi_{sq}I_{sd})\,(7)$$

B. TORQUE AND FLUX CONTROLLER

CDTC of induction motor drives requires two hysteresis controllers. The drive performance is influenced by the width of the hysteresis bands in terms of flux and torque ripples, current harmonics and switching frequency of power electronics devices [10]. Current distortion is reduced by small flux hysteresis band and torque ripple is reduced by small torque hysteresis bands.

$$H_\Psi = 1 \quad for \quad E_\Psi > +HB_\Psi\,(8)$$

$$H_\Psi = -1 \quad for \quad E_\Psi < -HB_\Psi\,(9)$$

Where *2HB$_\varphi$ is* hysteresis bandwidth of the controllers.

$$H_T = 1 \quad for \quad E_T > +HB_T\,(10)$$

$$H_T = -1 \quad for \quad E_T < -HB_T\,(11)$$

$$H_T = 0 \quad for \; -HB_T < E_T < +HB_T\,(12)$$

C. *SWITCHING SELECTION:*

Switching selection is based on H_Ψ, H_T and $S(K)$ is as per below table.

Table1 Applied selected voltage vector to inverter

H_Ψ	H_T	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
-1	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

IV.SPACE VECTOR MODULATION DTC STRATEGY

In space vector modulation strategy the three phase sinusoidal signals are transformed into a revolving voltage vector with a constant magnitude and angular frequency [11].
The main objectives of space vector pulse width modulation generated gate pulse are the following.
- ❖ Wide linear modulation range
- ❖ Less switching loss
- ❖ Less total harmonic distortion in the spectrum of switching waveform
- ❖ Easy implementation and less computational calculations

With the emerging technology in microprocessor the space vector modulation has been playing a pivotal and viable role in power conversion (Jenni and Wueest 1993). It uses a space vector concept to calculate the duty cycle of the switch which is imperative implementation of digital control theory of PWM modulators [12]-[16]. Before getting into the space vector modulation theory it is necessary to know about the harmonic analysis of power converters.
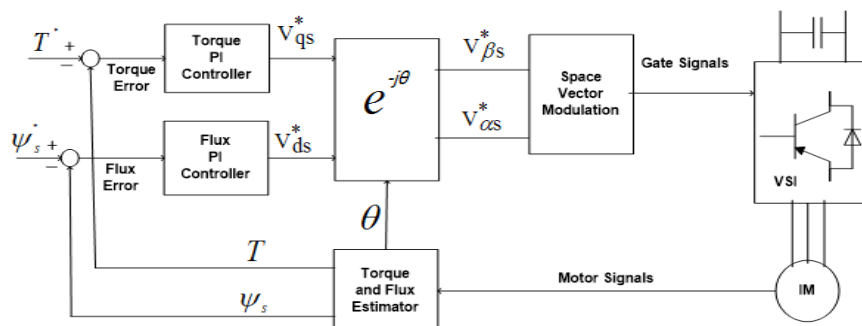

Fig. 3 Block diagram of space vector modulation DTC strategyapplied to induction motor

As shown above in Fig.3T^* and $\Psi_S^*$are used as command or desired speed and flux respectively [17]. Electromagnetic torque, and fluxare calculated in the same way as in classical direct torque control strategy.

A. IMPLEMENTATION PROCEDURE OF A TWO-LEVEL SPACE VECTOR MODULATION STRATEGY FOR INDUCTION MOTOR DRIVES:

The procedure for implementing a two-level space vector PWM can be summarized as follows:

1. Transform three phase quantities to two phase quantities: ABC to dq
2. Calculate the angle θ and reference voltage vector V_{ref} based on the input voltage components.

$$V_{ref} = \sqrt{(V_\alpha^2 + V_\beta^2)} \qquad (13)$$

The phase angle is evaluated from

$$\theta = tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \qquad (14)$$

3. Find the sector in which V_{ref} lies, and the adjacent space vectors of V_k and V_{k+1} based on the sector angle. (Where K = 1,2,.........5)

Table2 sector sextant

Sector	Degrees
1	$0^0 < \theta \le 60^0$
2	$60^0 < \theta \le 120^0$
3	$120^0 < \theta \le 180^0$
4	$180^0 < \theta \le 240^0$
5	$240^0 < \theta \le 300^0$
6	$300^0 < \theta \le 360^0$

5. Find the time intervals T_1, T_2 and T_0 based on T_Z and the angle (θ).

$$T_z V_{ref} = T_1 V_1 + T_2 V_2 \qquad (15)$$

$$T_1 = T_z a \frac{\sin\left(\frac{\pi}{3}-\alpha\right)}{\sin\left(\frac{\pi}{3}\right)} \qquad (16)$$

$$T_2 = T_z a \frac{\sin(\alpha)}{\sin\left(\frac{\pi}{3}\right)} \qquad (17)$$

$$T_0 = T_z - (T_1+T_2) \qquad (18)$$

$$Where$$
$$T_z = \frac{1}{f_z} \qquad a = \frac{V_{ref}}{\frac{2}{3}V_{dc}}$$

and T_1, T_2 and T_0 are dwell times for the vectors V_1, V_2 and V_0 respectively [18].

V. SIMULATION RESULTS AND DISCUSSION

Induction motor drive model is simulated as per parameters given in below:

Nominal Power = 150 KW, Rated Torque = 955 N, Stator voltage = 460 V, Frequency = 50 HZ
Stator Resistance = 14.85 mStator Leakage Inductance = 0.3027 mH, Rotor Resistance = 9.295 mΩ
Rotor Leakage Inductance = 0.3027 mH, Mutual Inductance = 10.46 mH

A. SIMULATION MODEL OF CLASSICAL DTC STRATEGY

The simulation of the classical DTC strategy is done in the discrete methodology. Inverter switching pluses are obtained from switching table and the hysteresis controllers logics. Motor flux and torque are estimated using the motor parameters such as stator voltages and currents.
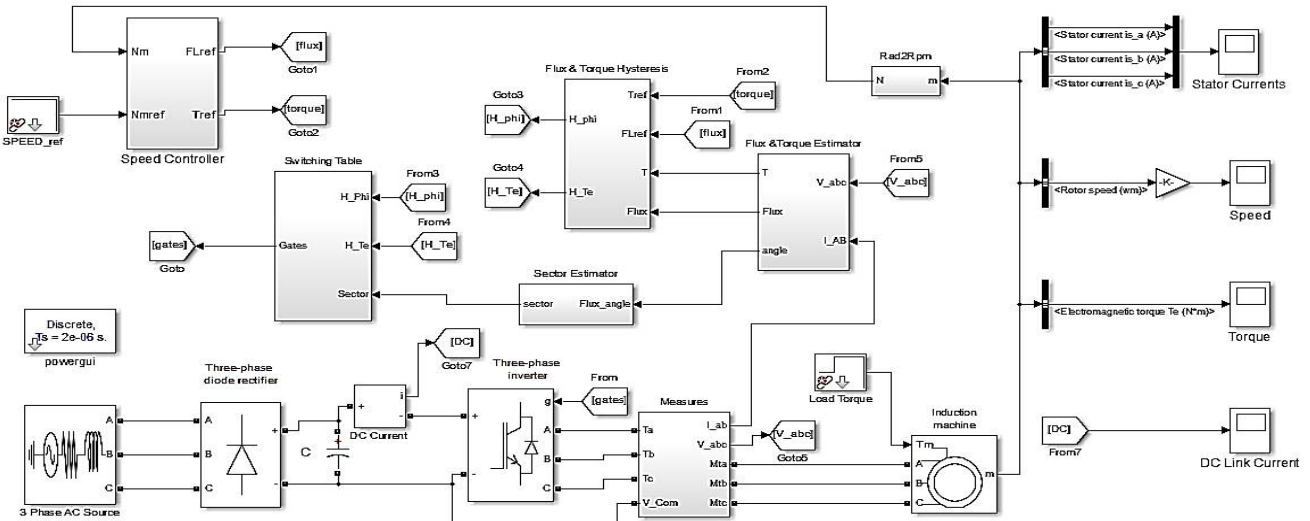
Fig.4 Simulink Model of Classical DTC

B. *SIMULATION MODEL OF SPACE VECTOR MODULATIONDTC STRATEGY*

In the simulinkmodel of space vector modulation DTC strategy the reference torque and flux both are calculated from the induction motor speed. There are flux and torque PI controller to compensate the steady state error and to produce the decoupling effect between torque and flux.IGBT switches are controlled by space modulation strategy.
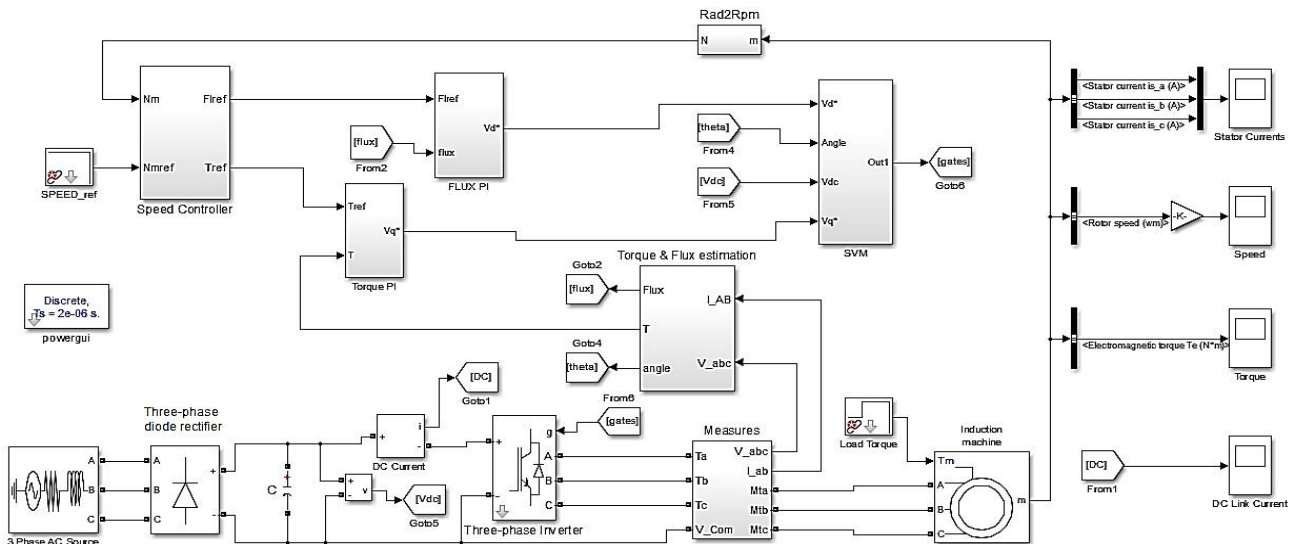

Fig.5 Simulink Model of Space Vector Modulation DTC

Classical and space vector modulation DTC Simulinkmodels are designed for the same induction motor parameters.

C. SIMULATION RESULTS OF CLASSICAL DTC STRATEGY
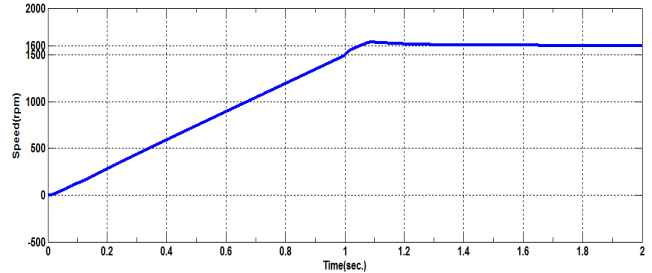

Fig. 6 Stator Currents in Classical DTC

Fig. 7 Speed in Classical DTC

Initially stator currents of induction motors are more than the steady state currents, this condition occurs due to inductance of the induction motor. Speed is varying linearly upto 1 second after that it is more than the synchronous speed i.e. (1500rpm) for regenerative braking.
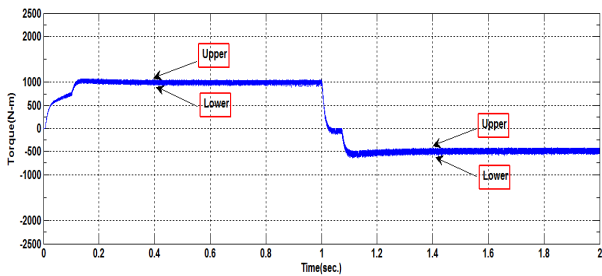

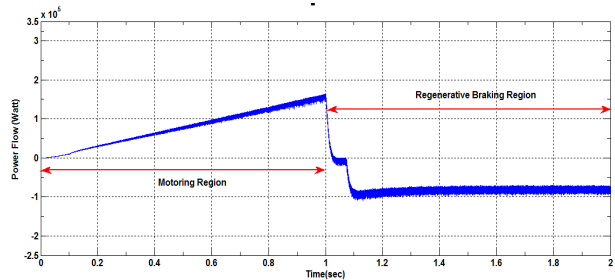
Fig.8 Torque in Classical DTC

Fig.9 Power Flow in Classical DTC

Torque and power flow both are positive in forward motoring region and negative in the regenerative braking region. Power flow in the regenerative braking is from load to source side.

Reference to theFig.8torque ripple for motoring and regenerative braking mode is calculated as below:

Peak to peak torque ripple in motoring mode (0 to 1 second) = 1080-910

$$= 170 \text{ N-m.} \quad (19)$$

Regenerative mode peak to peak torque ripple =(-400)-(-600)

$$= 200 \text{ N-m.} \quad (20)$$

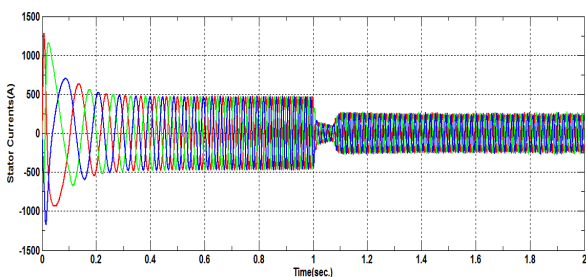*D.SIMULATION RESULTS OF SPACE VECTOR MODULATION DTC STRATEGY*
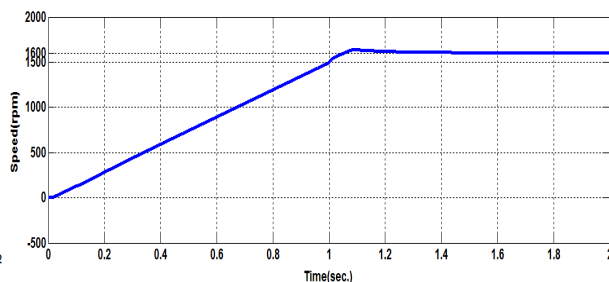

Fig. 10Stator Currents in SVM-DTC

Fig. 11 Speed in SVM-DTC

Speed variation for space vector modulation DTC is same as the classical direct torque control strategy, Because of inputs applied to the speed control unit are same for both strategies.
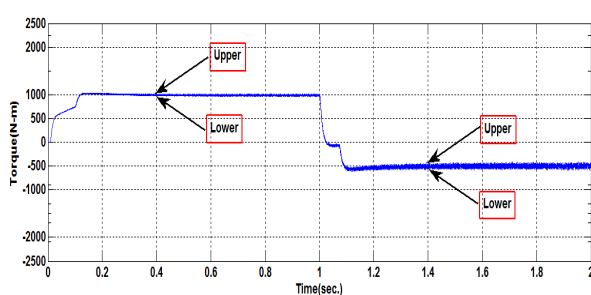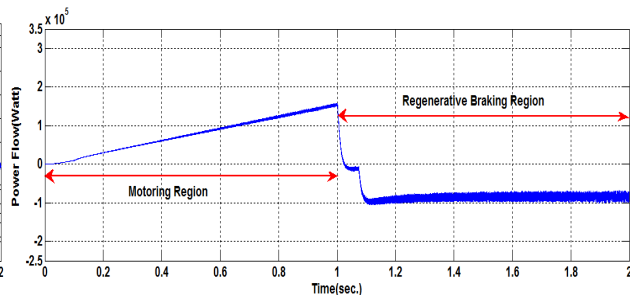

Fig. 12 Torque in SVM-DTC

Fig. 13 Power Flow in SVM-DTC

Reference to Fig.13, between time 0 to 1 seconds drive is operating in motoring mode and in the time range 1 to 2 seconds drive is operating in the regenerative braking mode.Power flow in the motoring mode is positive and negative for regenerative braking mode.

Torque ripple reference to the Fig.12 is calculated as following:

Peak to peak torque ripple in motoring mode (0 to 1 second) =1040-950

$$= 90 \text{ N-m.} \tag{21}$$

Regenerative mode peak to peak torque ripple =(-460)-(-564)

$$= 104 \text{ N-m.} \tag{22}$$

Henceaccording to relation (19)-(22) toque ripple in SVM-DTC is reduced as compared to the classical DTC for both motoring and regenerative braking region. Hence it can be observed that space vector modulation DTC strategy is superiorthanthe classical DTC strategy.

VI.CONCLUSIONS

In this paper, regenerative braking of induction motor drive is explained with the help of simulation results for classical and space vector modulation strategies. Following conclusions are derived from simulink results:

(1) Inverter switching frequency is variable in the classical DTC due to presence of the hysteresis controller, space vector modulation DTC strategy provides the constant switching frequency.

(2)It is realized that induction motor drive operation under the space vector modulation direct torque control strategy gives reduced torque ripple as compared to classical direct torque control strategy for the entire load and speed range.

(3)In the classical direct torque control strategy a single voltage vector is applied during one sampling time, for space vector modulation direct torque control strategy a sequence of the six vectors is applied during the same time. This is the merit of space vector modulation direct torque control strategy due to reduced harmonics.

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