

Improvement of Direct torque control Performance by using Discrete SVM Techniques

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Abstract— Direct torque is a control technique used in a AC drive systems to obtain high performance torque control. The low number of voltage vectors which can be applied to the machine using the basic DTC scheme may cause undesired torque and current ripple. In order to reduce the torque, flux, current and speed ripple a Discrete Space Vector Modulation (DSVM-DTC) is implemented. DSVM-DTC, use a kind of space vector modulation to produce more voltage vectors than are available with the classical DTC. The performance of this control methods has been demonstrated by simulation with MATLAB/SIMULINK..

Index Terms— Direct torque control, Discrete space vector modulation, induction motor, torque and current ripple, voltage vectors.

1 INTRODUCTION

Alternating current motors are getting more and more popular for applications in industrial environments. Particularly in speed control systems, ac induction motors are more widely used nowadays due to the characteristics of higher efficiency, less inertia, smaller volume and lower cost. The capabilities to operate at higher speeds, higher torques and larger power ratings make the induction motors more attractive than dc motors for medium and high power motor drives.

In recent years, research interest in IM sensorless drives has grown significantly due to some of their advantages, such as mechanical robustness, simple construction and maintenance [6]. Present efforts are devoted to improve the sensorless operation, especially for low speed and to develop robust control strategies.

The DTC is one of the actively researched control schemes which are based on the decoupled control of stator flux and torque providing a quick and robust response with high and low speed present notable torque, flux, current and speed ripple.

In this paper a new control technique, DSVM-DTC is introduced which allows the performance of DTC scheme in terms of flux and torque ripple and current distortion to be improved. These results can be achieved without increasing the complexity of the power circuit and the inverter switching frequency.

Sections II and III presents the proposed direct torque control strategy and direct torque control of induction motor based on discrete space vector modulation strategy. Section IV gives the simulation results of the proposed methods. Finally, conclusions are given in section V.

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II. DIRECT TORQUE CONTROL STRATEGY

Direct torque control (DTC) has become an alternative to the well known Vector Control of induction machine. It was introduced in Japan by Takahashi (1984) and also in Germany by Depenbrock (1985). DTC of induction machine has increasingly become the best alternative to field orientation methods or vector control. The Direct Torque Control (DTC) method is characterised by its simple implementation and a fast dynamic response. The main advantages of DTC are absence of coordinate transformation and current regulator absence of separate voltage modulation block [1].

A block diagram of a DTC system for an induction machine is shown in Figure. 1[2]. DTC scheme uses a stationary $d-q$ reference frame. Torque and flux are controlled by the stator voltage space vector defined in this reference frame.

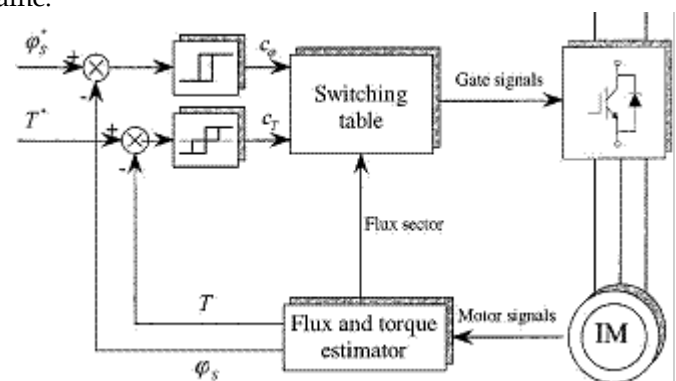


Figure. 1: Direct torque control of induction machine

In principle the DTC selects one of the six voltage vectors and two zero voltage vectors generated by a VSI in order to keep stator flux and torque within the limits of two hysteresis bands. The presence of hysteresis controllers leads to a variable switching frequency operation. In addition, the basic DTC scheme may cause undesired torque and current ripple. The use of a switching table for voltage vector selection provides fast torque response, low inverter switching frequency and low harmonic losses. The DTC controller consists of two hysteresis comparator (flux and torque) to select the switching voltage vector in order to maintain flux and torque between upper and lower limit.

A. DTC development

The develop torque control of inverter fed induction machine is carried out by hysteresis control of magnitude stator flux and torque that selects one of the six non-zero and two zero inverter voltage vectors shown in Fig. 2. The selection is made in order to maintain torque and flux error inside the hysteresis band in which the errors are indicated by ΔT_e and $\Delta \psi_s$ respectively. Noting that

$$\Delta T_e = T_{eref} - T_e \quad (1)$$

$$\Delta \psi_s = \psi_{sref} - \psi_s \quad (2)$$

The operation may be described by the following manner:

- Sa=1 means top switch closed, bottom switch opened.
- Sa=0 means top switch opened, bottom switch closed

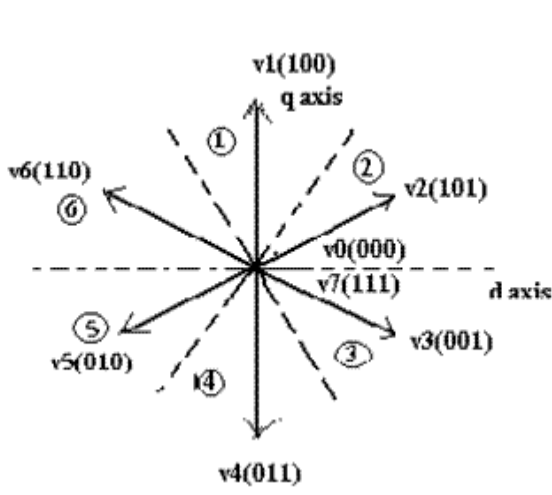


Figure. 2: Inverter output voltage vectors

B. Electromagnetic torque control

The electromagnetic torque value resulting from the previous stage is then compared with the electromagnetic torque reference, using the three level hysteresis comparator, represented in figure 3. In this manner, the result may be increase, decrease or maintain the torque, depending on the comparator output [3].

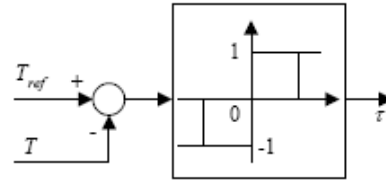
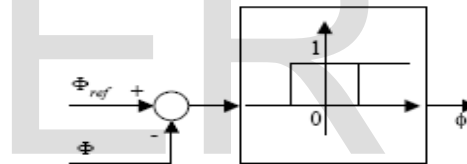


Figure 3. Three level hysteresis comparator: $\tau = 1 \Rightarrow$ increase torque; $\tau = 0 \Rightarrow$ maintain torque; $\tau = -1 \Rightarrow$ decrease torque.

C. Stator flux control

In a similar way, the flux value will be compared with a flux reference, but using a two level hysteresis comparator, shown in figure 4. The result will be used to increase or decrease the flux [3].



Switching vector selection

It is necessary to know the angular sector in which the actual flux is located. The actual position can be determined by Equation (3), from the orthogonal flux components:

$$\theta_{fs} = \tan^{-1}(\Phi_{qs} / \Phi_{ds}) \quad (3)$$

The θ angle returned by Equation (3) determines the sector where the flux is, (figure 2).

TABLE.1 SWITCHING TABLE FOR CONVENTIONAL DTC

| T | θ | 1 | 2 | 3 | 4 | 5 | 6 |
|----|----------|----|----|----|----|----|----|
| -1 | 0 | V5 | V4 | V3 | V2 | V1 | V6 |
| 0 | 0 | V0 | V7 | V0 | V7 | V0 | V7 |
| 1 | 0 | V3 | V2 | V1 | V6 | V5 | V4 |

| | | | | | | | |
|----|---|----------------|----------------|----------------|----------------|----------------|----------------|
| -1 | 1 | V ₆ | V ₅ | V ₄ | V ₃ | V ₂ | V ₁ |
| 0 | 1 | V ₇ | V ₀ | V ₇ | V ₀ | V ₇ | V ₀ |
| 1 | 1 | V ₂ | V ₁ | V ₆ | V ₅ | V ₄ | V ₃ |

Sector calculation-

$0 \leq \theta_{fs} \leq 60$ (sector 2)

$-60 \leq \theta_{fs} \leq 0$ (sector 3)

$-120 \leq \theta_{fs} \leq -60$ (sector 4)

$-180 \leq \theta_{fs} \leq -120$ (sector 5)

$120 \leq \theta_{fs} \leq 180$ (sector 6)

$60 \leq \theta_{fs} \leq 120$ (sector 1)

The combination of the comparators outputs and the sector is then applied to an optimal switching table (Table 1) which will give the voltage vector to be applied to the inverter.

III. DIRECT TORQUE CONTROL OF INDUCTION MOTOR BASED ON SPACE VECTOR MODULATION STRATEGY

The main idea the DSVM-DTC control strategy is to force the torque and stator flux to approach their reference by applying in one sampling period several voltage vectors instead of only one voltage vector as in basic DTC.[7]

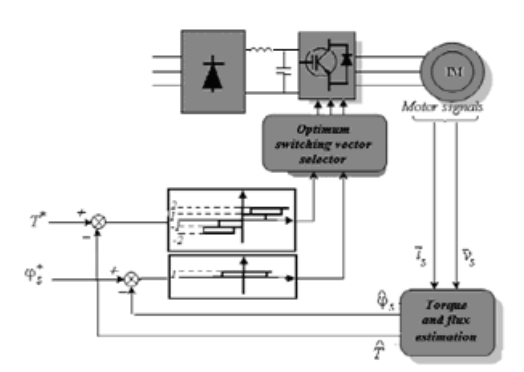


Figure 5: DSVM-DTC control scheme.

This control algorithm uses prefixed time intervals within a cycle period and in this way a higher number of voltage space vectors can be synthesized with respect to those used in basic DTC technique. The increased number of voltage vectors allows the definition of switching tables according to the rotor speed, the flux and torque errors. With DSVM-DTC strategy, 19 voltage vectors can be selected for each sector, according to the rotor speed, the flux and the torque errors range as is represented in Figure.6 and TABLE 2. The switching period is divided into three equal time intervals and one voltage vector is applied at each time interval.

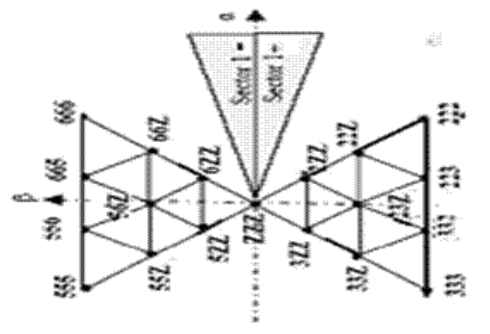


Figure.6 voltage vector obtained by using DSVM with three equal time interval

A. Speed voltage

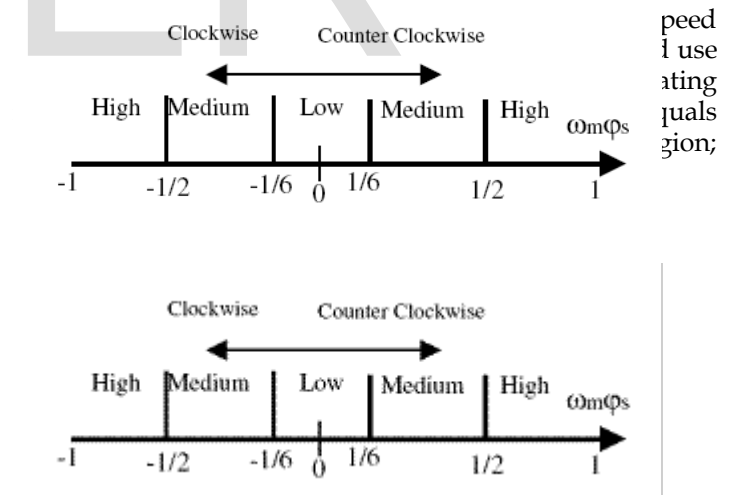


Figure 7: Speed voltage regions.

The voltage induced is

$$\omega_r = \begin{bmatrix} \Phi_{sd} \\ -\Phi_{sq} \end{bmatrix}$$

But only its value is used, so calculated voltage is

$$V_s = \omega_r \Phi_s$$

This is then compared to the regions.

B. Sector calculation

The DSVM use twelve sectors instead of six; all of the six sectors in DTC are divided in half. The finer division of sectors is used in the high-speed region. At medium and low speed range only six sectors are used, Show figure .8

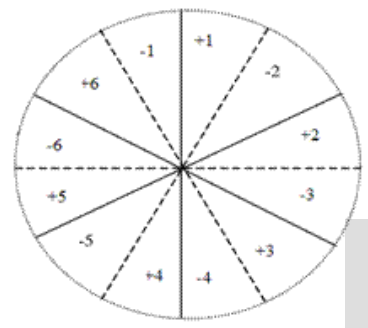


Figure.8 DSVM sectors

C. Torque hysteresis

The DSVM can produce more voltage vectors which if properly applied produce less ripple. To achieve this, the torque hysteresis has 5 levels instead of two. Figure8. If torque error is small hysteresis is in state 0. In this case a voltage vector is chosen trying to maintain torque at its actual level. If hysteresis is in state +/- 1, a vector just as big as to push torque into the small region is chosen. When hysteresis is in state +/- 2, a vector compensating for the error as fast as possible is chosen, i.e. the same vectors used in the classical DTC [1].

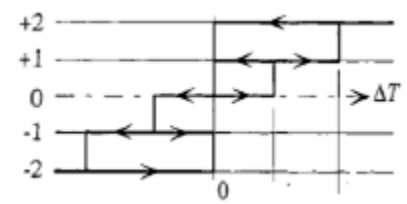


Figure .9: 5-level hysteresis comparator

TABLE 2: LOOK UP TABLES

1-low speed voltage

| T | θ | 1 | 2 | 3 | 4 | 5 | 6 |
|----|---|-----|-----|-----|-----|-----|-----|
| -2 | 0 | 555 | 444 | 333 | 222 | 111 | 666 |
| -1 | 0 | 5ZZ | 4ZZ | 3ZZ | 2ZZ | 1ZZ | 6ZZ |
| 0 | 0 | ZZZ | ZZZ | ZZZ | ZZZ | ZZZ | ZZZ |
| 1 | 0 | 3ZZ | 2ZZ | 1ZZ | 6ZZ | 5ZZ | 4ZZ |
| 2 | 0 | 333 | 222 | 111 | 666 | 555 | 444 |
| -2 | 1 | 666 | 555 | 444 | 333 | 222 | 111 |
| -1 | 1 | 6ZZ | 5ZZ | 4ZZ | 3ZZ | 2ZZ | 1ZZ |
| 0 | 1 | ZZZ | ZZZ | ZZZ | ZZZ | ZZZ | ZZZ |
| 1 | 1 | 2ZZ | 1ZZ | 6ZZ | 5ZZ | 4ZZ | 3ZZ |
| 2 | 1 | 222 | 111 | 666 | 555 | 444 | 333 |

2-medium speed voltage

| T | θ | 1 | 2 | 3 | 4 | 5 | 6 |
|----|---|-----|-----|-----|-----|-----|-----|
| -2 | 0 | 555 | 444 | 333 | 222 | 111 | 666 |
| -1 | 0 | ZZZ | ZZZ | ZZZ | ZZZ | ZZZ | ZZZ |
| 0 | 0 | 3ZZ | 2ZZ | 1ZZ | 6ZZ | 5ZZ | 4ZZ |
| 1 | 0 | 33Z | 22Z | 11Z | 66Z | 55Z | 44Z |
| 2 | 0 | 333 | 222 | 111 | 666 | 555 | 444 |
| -2 | 1 | 666 | 555 | 444 | 333 | 222 | 111 |
| -1 | 1 | ZZZ | ZZZ | ZZZ | ZZZ | ZZZ | ZZZ |
| 0 | 1 | 2ZZ | 1ZZ | 6ZZ | 5ZZ | 4ZZ | 3ZZ |
| 1 | 1 | 22Z | 11Z | 66Z | 55Z | 44Z | 33Z |
| 2 | 1 | 222 | 111 | 666 | 555 | 444 | 333 |

3-high speed voltage (+1 sector)

| T | θ | 1 | 2 | 3 | 4 | 5 | 6 |
|----|---|-----|-----|-----|-----|-----|-----|
| -2 | 0 | 555 | 444 | 333 | 222 | 111 | 666 |
| -1 | 0 | 3ZZ | 2ZZ | 1ZZ | 6ZZ | 5ZZ | 4ZZ |
| 0 | 0 | 33Z | 22Z | 11Z | 66Z | 55Z | 44Z |
| 1 | 0 | 333 | 222 | 111 | 666 | 555 | 444 |
| 2 | 0 | 333 | 222 | 111 | 666 | 555 | 444 |
| -2 | 1 | 666 | 555 | 444 | 333 | 222 | 111 |
| -1 | 1 | 2ZZ | 1ZZ | 6ZZ | 5ZZ | 4ZZ | 3ZZ |
| 0 | 1 | 23Z | 12Z | 61Z | 56Z | 45Z | 34Z |
| 1 | 1 | 223 | 112 | 661 | 556 | 445 | 334 |
| 2 | 1 | 222 | 111 | 666 | 555 | 444 | 333 |

4-high speed voltage (-1sector)

| T | θ | 1 | 2 | 3 | 4 | 5 | 6 |
|----|---|-----|-----|-----|-----|-----|-----|
| -2 | 0 | 555 | 444 | 333 | 222 | 111 | 666 |
| -1 | 0 | 3ZZ | 2ZZ | 1ZZ | 6ZZ | 5ZZ | 4ZZ |
| 0 | 0 | 23Z | 12Z | 61Z | 56Z | 45Z | 34Z |
| 1 | 0 | 33Z | 22Z | 11Z | 66Z | 55Z | 44Z |
| 2 | 0 | 333 | 222 | 111 | 666 | 555 | 444 |
| -2 | 1 | 666 | 555 | 444 | 333 | 222 | 111 |
| -1 | 1 | 2ZZ | 1ZZ | 6ZZ | 5ZZ | 4ZZ | 3ZZ |
| 0 | 1 | 22Z | 11Z | 66Z | 55Z | 44Z | 33Z |
| 1 | 1 | 222 | 111 | 666 | 555 | 444 | 333 |
| 2 | 1 | 222 | 111 | 666 | 555 | 444 | 333 |

D. Look-up table

The look-up table in this case has four input variables; flux and torque hysteresis state, sector number and speed voltage. Since the system chose voltage vectors depending on the emf, each speed region uses different switch tables (Table2). When the system operates in the high speed region two switch tables for each sector are used. Because the emf introduces an asymmetry, the switch tables also become asymmetric. Hence, different tables must be used for positive and negative rotational directions. For example; the label "23Z" denotes the voltage vector which is synthesized by using the voltage space vectors V_2 , V_3 and V_0 or V_7 , each one applied for one third of the cycle period.

IV.SIMULATION RESULTS

The performance of this control methods have been demonstrated by simulations with MATLAB/SIMULINK (matlab7.1) package. The results of simulation of DTC and DSVM_DTC of induction motor are shown in Figure 10, 11,12 and 13 respectively.

The simulation results show that flux and torque responses are very rapid for two DTC methods. By DSVM_DTC technique shown in figure 11b, the ripple of torque in steady state is reduced remarkably compared with DTC, the torque changes through big oscillation and the torque ripple is bigger in DTC shown Figure 11a. However, the large torque ripple in steady-state operation is one of its major drawbacks.

The improved DTC system, DSVM, can produce more voltage space vectors than the basic DTC Figure 10a and 10b. The larger number of space vectors are used to decrease torque ripple in steady-state operation.

We can observe an optimal reduction of the flux oscillations, as shown in Figure.12b, that the stator flux trajectory of the DSVM_DTC is more approximately circle than it of the conventional DTC shown in Figure 12.a, consequently, as illustrated in Figure.13b, the current have less harmonic distortion that compared with DTC shown in Figure13a.

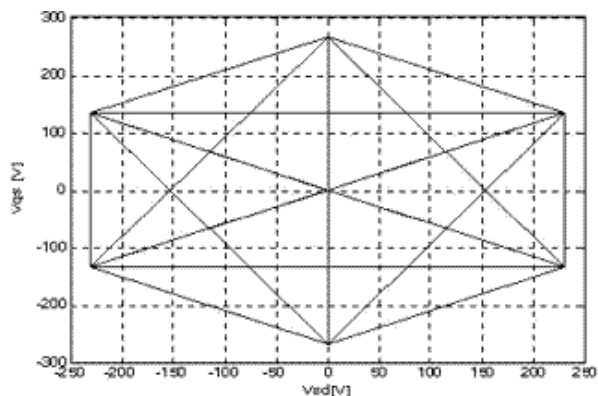


Figure10.a stator voltage in DTC

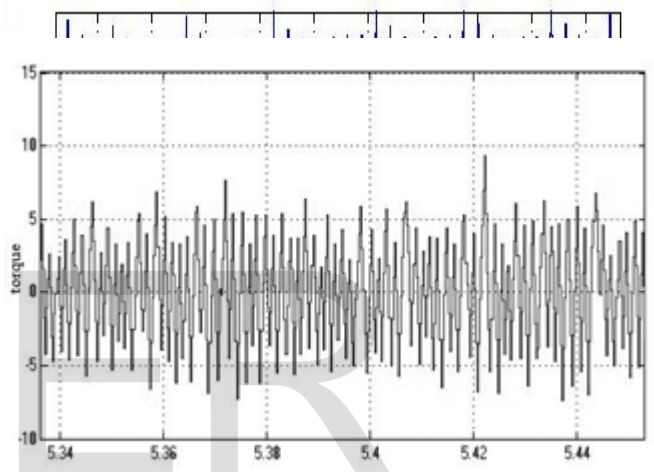
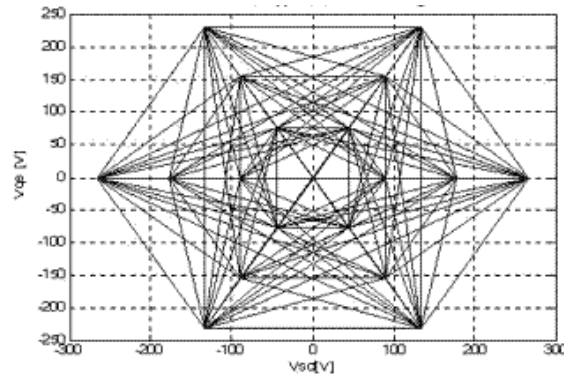


Figure.11 a. Torque response in DTC

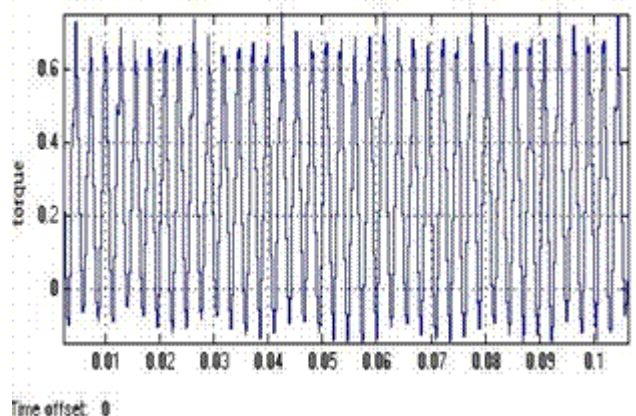


Figure.11b .torque response in DSVM-DTC

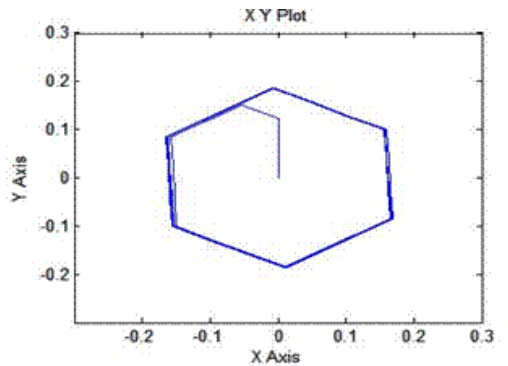


Figure12.a the stator flux circle DTC

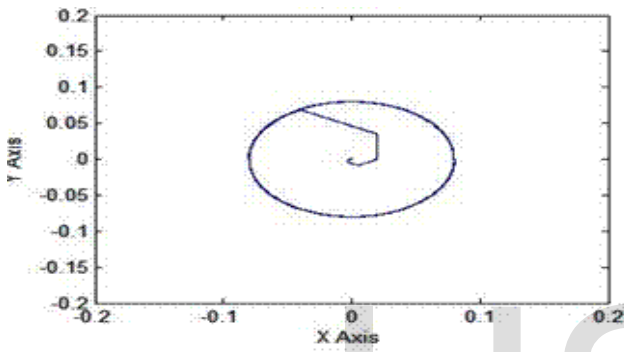


Figure12.b the stator flux circle DSVM-DTC

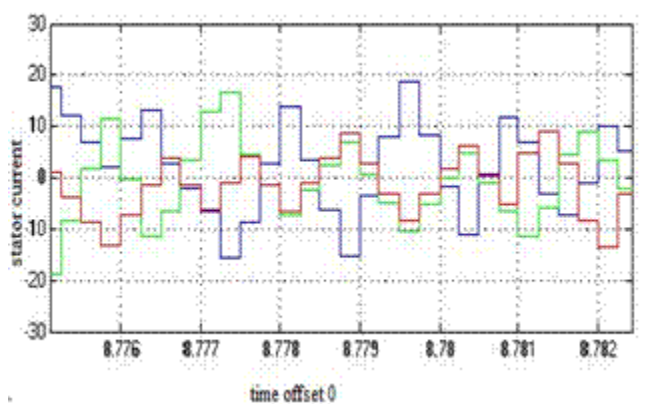
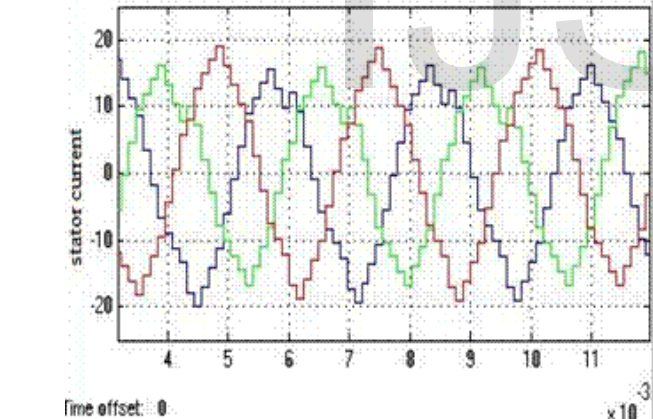


Figure13.b the stator current (I_{abc}) DSVM-DTC

V. CONCLUSION

Direct Torque Control of induction motor is one of the modern techniques used for speed and torque control of induction motor. The low number of voltage vectors which can be applied to the machine using the basic DTC scheme may cause undesired torque and current ripple. This drawback is avoided by using DSVM-DTC. Both DTC and DSVM-DTC are simulated using simulink. The large number of voltage vectors used in DSVM-DTC would improve performance in terms low ripple, but they would require large and complex look-up table.

APPENDIX

The parameters of induction motor are as follows:

| | |
|------------------------|------------|
| Power rating | : 3hp |
| Rated voltage | : 220V |
| Pole pair | : 2 |
| Stator resistance | : 0.435ohm |
| Stator inductance | : 0.0022H |
| Rotor resistance | : 0.861ohm |
| Rotor inductance | : 0.002H |
| Magnetizing inductance | : 0.06931H |
| Inertia | : 0.089 |
| Reference speed | : 1750rpm |

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