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Torque Ripple Minimization in Direct Torque Control of Induction Motor using SVPWM Technique

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Abstract- *The conventional DTC (CDTC) drive contains a pair of hysteresis comparators, a flux and torque estimator and a voltage vector selection table. The movement of stator flux vector during the changes of cyclic sectors is responsible for creating notable edge oscillations of electromagnetic torque. Another great issue is the implementation of hysteresis controllers which requires a high sampling frequency.*

This paper is aimed to analyze DTC principles, the strategies and the problems related to its implementation and the possible improvements using Space Vector Pulse Width Modulation (SVPWM). In SVPWM for each sampling period the switching instants of different space vectors are determined to reduce torque ripple. A comparison study between SVPWM-DTC and CDTC is carried out to apply switching select voltage vector. The theoretical foundation principle, the numerical simulation procedure and the performances of both methods are also presented.

Keywords—CDTC,SVPWM, Hysteresis control, Space vector, Torque ripple

I. INTRODUCTION

Direct Torque Control was first introduced by Takahashi in 1986[1]. The principle is based on limit cycle control and it enables both quick torque response and efficiency operation. The basic disadvantages of DTC scheme using hysteresis controllers are the variable switching frequency, the current and torque ripple. The movement of stator flux vector during the changes of cyclic sectors is responsible for creating notable edge oscillations of electromagnetic torque. Another great issue is the implementation of hysteresis controllers which requires a high sampling frequency. When an hysteresis controller is implemented using a digital signal processor (DSP) its operation is quite different to the analogue one. In the analogue operation the value of the electromagnetic torque and the magnitude of the stator flux are limited in the exact desirable hysteresis band. That means, the inverter can change state each time the torque or the flux magnitude are throwing the specified limits. On the other way, the digital implementation uses specific sample time on which the magnitudes of torque and flux are checked to be in the desirable limits. That means, very often, torque and flux can be out of the desirable limits until the next sampling period. For this reason, an undesirable torque and flux ripple is occurred.

In SVPWM two active vectors surrounded by two null vectors are applied in each sector. Also, the DTC-SVM can be applied using closed loop torque control, for minimization of torque ripple . In this case estimation of stator and rotor flux is required. Voltage is always applied perpendicular to the flux vector. In this method vector is applied at perpendicular direction to stator flux linkage vector. This produces change in torque and flux. This changes produced by applied voltage vectors in electromagnetic torque and stator flux are used to modify the vector table.

II. THE CONVENTIONAL DTC

The basic configuration of the conventional DTC drive proposed by Takahashi is as shown in Fig. 1. It consists of a pair of hysteresis comparator, torque and flux estimators, voltage vector selector and a Voltage Source Inverter (VSI). DTC performs separate control of the stator flux and torque, which is also known as decouple control. The core of this control method is to minimize the torque and flux errors to zero by using a pair of hysteresis comparators. The hysteresis comparators lie at the heart of DTC scheme not only to determine the appropriate voltage vector selection but also the period of the voltage vector selected. The performance of the system is directly dependent on the estimation of stator flux and torque. Inaccurate estimations will result in an incorrect voltage vector selection. The basic method for estimating the stator flux is by using the stator voltage model. This model does not require rotor speed and only need a single machine parameter, i.e. the stator resistance

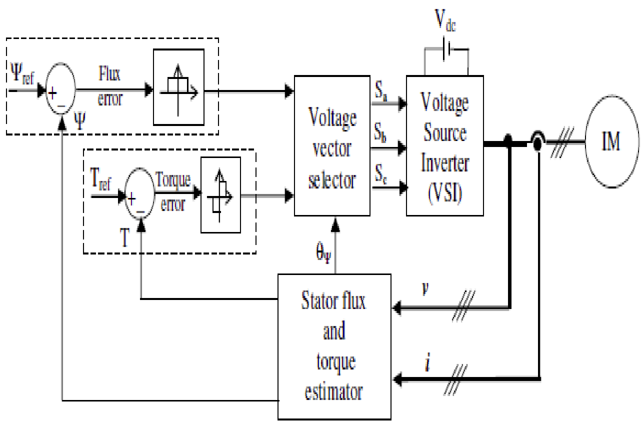

Fig.1 Conventional DTC drive configuration

According to the combination of the switching modes, the voltage vectors are specified for eight different voltage vectors. The switching vectors associated with DTC are shown in Fig. 2. There are six active voltage vectors $(V_1 - V_6)$ and two zero voltage vectors (V_0 and V_7) at the origin. It can be shown that the voltage vector is given by

$$V_s = \frac{2}{3} V_{dc}\,(S_a + S_b e^{\frac{2\pi}{3}} + S_c e^{4\pi/3}) \text{ ------ (1)}$$

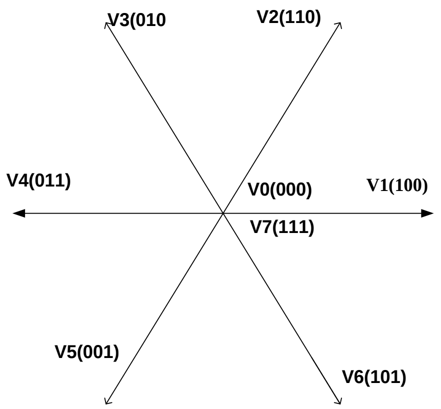

Fig. 2 Voltage space vector

A Direct Flux Control

The stator flux in stationary frame can be written as

$$\Psi_s = \int (V - R_s . i_s) \qquad \text{----- (2)}$$

Analysis is simplified if the stator resistance voltage drop is neglected; hence the flux variation direction is fixed along the selected voltage vector. Over a small period of time, it can be written as

$$\Delta\psi_s = v_s .\mathrm{dt} \qquad \text{----- (3)}$$

The magnitude and orientation of the stator flux must be known in order to directly control the stator flux by selecting appropriate voltage vector .It is proposed that the stator flux plane is divided into six sectors. Each sector will have a different set of voltage vectors to increase (voltage vector highlighted in gray) or decrease (voltage vector highlighted in black) the stator flux as illustrated in Fig. 3.

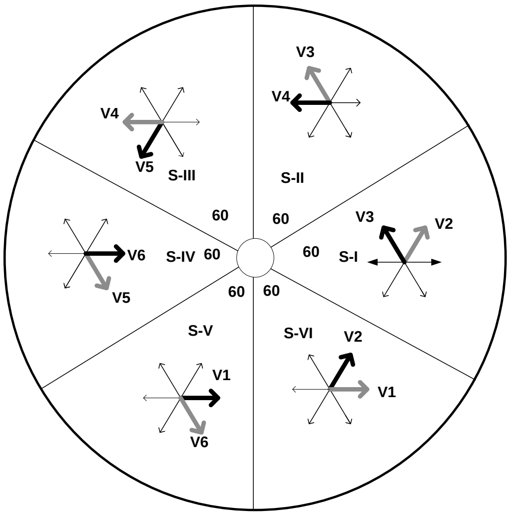

Fig. 3 six equally sectors with different set of voltage vector

If the stator flux lies in sector k then the voltage vector V_{k+1} or V_{k+2} can be selected to increase or decrease the stator flux. The radial voltage vectors (V_k, and V_{k+3}), which can be used to quickly affect the flux, are generally avoided.

The estimated stator flux is subtracted from the corresponding reference values to obtain the error, which is then fed to the hysteresis comparator .The hysteresis comparator will produce flux error status, which can be either 1 or 0.

B Direct Torque Control

Equation (4) gives the instantaneous torque in terms of stator and rotor flux linkages.

$$T_e = \frac{3}{2}\frac{L_m}{L_s L_r}\Psi_s\Psi_r = \frac{3}{2}\frac{L_m}{L_s L_r}\sin\theta_{SR} \qquad \text{-----} (4)$$

The above equation shows that, in order to obtain high dynamic performance it is necessary to vary θ_{SR} quickly. The analysis of the variation θ_{SR} and the electromagnetic torque with the application of different voltage vectors is discussed. It can be summarized that, assuming the rotor is rotating counterclockwise continuously, the stator flux, which lies in sector k, plays an important role in controlling θ_{SR} by applying an appropriate voltage vector as tabulated in Table 1.

In DTC, the torque is controlled within its hysteresis band similar to the stator flux. Three-level hysteresis comparator is employed because the machine may operate in motoring mode as well as braking mode.

Table 1 The variation of θsr with different voltage vector

Voltage vector	Effect on stator flux	θ_{SR} and T_e
Active Forward V_{k+1} and V_{k+2}	Ψ_s advance forward	Increase
Zero V_0 V_7	Ideally Ψ_s freezes Practically Ψ_s weakens due to R_s drop	Decrease
Radial V_k and V_{k+3}	Ψ_s increase or Decrease rapidly	Decrease
Reverse active V_{k-1} and V_{k-2}	Ψ_s rotate in reverse direction	Decrease rapidly

C Switching Selection

Due to the decoupled control of torque and stator flux in DTC, a high performance torque control can be established. If the stator flux lies in sector k with the motor rotating in counter clockwise, active voltage vector V_{k+1} is used to increase both the stator flux and torque. V_{k+2} is selected to increase the torque but decrease the stator flux. The two zero voltage vectors (V_0 and V_7) are used to reduce the torque and at the same time, freezes the stator flux. Reverse voltage vector V_{k-2} is used to decrease the torque and flux in forward braking mode. Whereas V_{k-1} will reduce the torque and increase the flux.

Table 2 Voltage vector selection table

	Flux Error status	Torque Error status	SI	SII	SIII	SIV	SV	SVI
Counter clockwise	1	1	V_2	V_3	V_4	V_5	V_6	V_1
		0	V_0	V_7	V_0	V_7	V_0	V_7
		-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_7	V_0	V_7	V_0	V_7	V_0
		-1	V_5	V_6	V_1	V_2	V_3	V_4
Clockwise	1	1	V_6	V_1	V_2	V_3	V_4	V_5
		0	V_7	V_0	V_7	V_0	V_7	V_0
		-1	V_2	V_3	V_4	V_5	V_6	V_1
	-1	1	V_5	V_6	V_1	V_2	V_3	V_4
		0	V_0	V_7	V_0	V_7	V_0	V_7
		-1	V_3	V_4	V_5	V_6	V_1	V_2

Here Active Switching vector V_1(100), V_2 (110), V_3 (010), V_4 (011), V_5 (001), V_6(101). Null switching vector V_0(000), V_7(111)

Small torque hysteresis band is ideal to produce a smooth torque. However for microprocessor-based implementation, if the hysteresis band is set too small, the torque may overshoot and touch the upper band. Once it exceeds the upper band the hysteresis comparator will produce a signal that will select a reverse voltage vector instead of zero voltage vector to reduce the torque .Due to this incorrect voltage vector selection, the undershoot may occur and as a result, the torque ripple is increased drastically.

III. THE PROPOSED SVPWM- DTC

Space vector PWM refers to a special switching scheme of the six power semiconductor switches of a three phase power converter. Space vector PWM (SVPWM) has become a popular PWM technique for three-phase voltage-source inverters in applications such as control of induction and permanent magnet synchronous motors. The drawbacks of the sinusoidal PWM and hysteresis-band current control are reduced using this technique. Instead of using a separate modulator for each of the three phases as in the PWM techniques, the complex reference voltage vector processed as a whole. The complete block diagram is shown in Fig.-4.

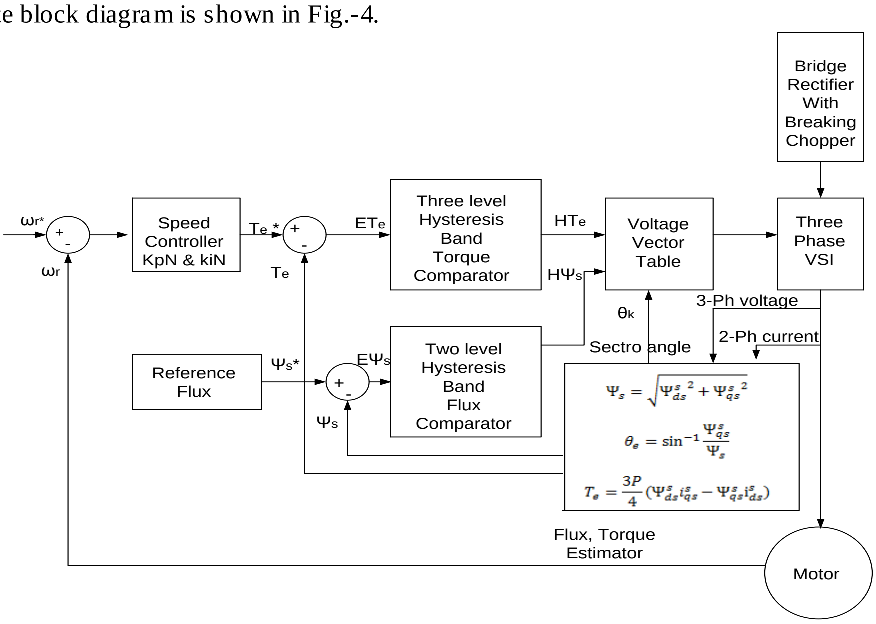

Fig. 4 SVPWM- DTC drive configuration

Therefore, the interaction between the three motor phases is considered. It has been shown to generate fewer harmonics distortion in the output voltages and or currents applied to the phases of an AC motor and to provide more efficient use of supply voltage compared with sinusoidal modulation technique as shown in Fig. 5.

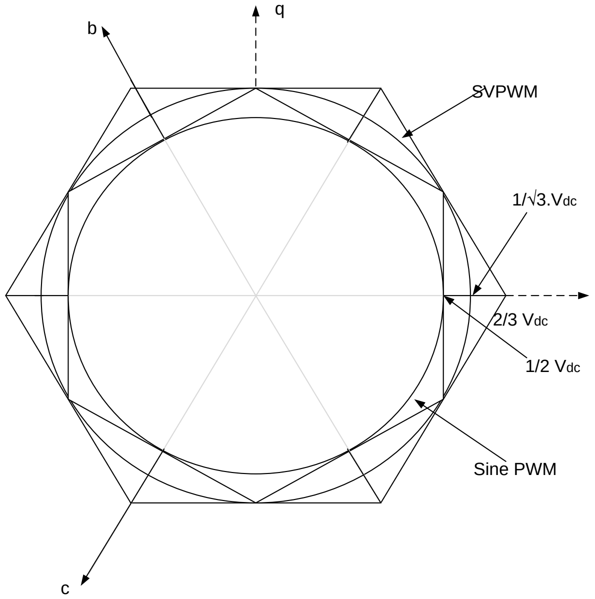

Fig. 5 Locus of comparison for maximum linear control voltage in Sine PWM and SVPWM.

A Principle of Space Vector Pulse Width Modulation

In this modulation technique the three phase quantities can be transformed to their equivalent two-phase quantity either in synchronously rotating frame (or) stationary frame. From these two-phase components, the reference vector magnitude can be found and used for modulating the inverter output.

To implement the space vector PWM, the voltage equations in the *abc* reference frame can be transformed into the stationary *dq* reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Fig. 6.

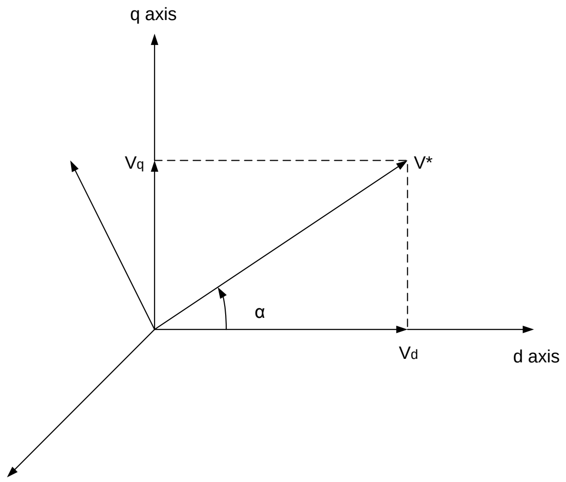

Fig.6. The relationship of abc reference frame and stationary dq reference frame.

As described in Fig. 6, this transformation is equivalent to an orthogonal projection of $[a, b,c]^t$ onto the two-dimensional perpendicular to the vector $[1, 1, 1]^t$ (the equivalent d-q plane) in a three-dimensional coordinate system. As a result, six non-zero vectors and two zero vectors are possible. Six nonzero vectors (V1 - V6) shape the axes of a hexagonal as depicted in Figure 5.3, and feed electric power to the load. The angle between any adjacent two non-zero vectors is 60°. Meanwhile, two zero vectors (V0 and V7) are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by V0, V1, V2, V3, V4, V5, V6, and V7. The same transformation can be applied to the desired output voltage to get the desired reference voltage vector V^* in the d-q plane.

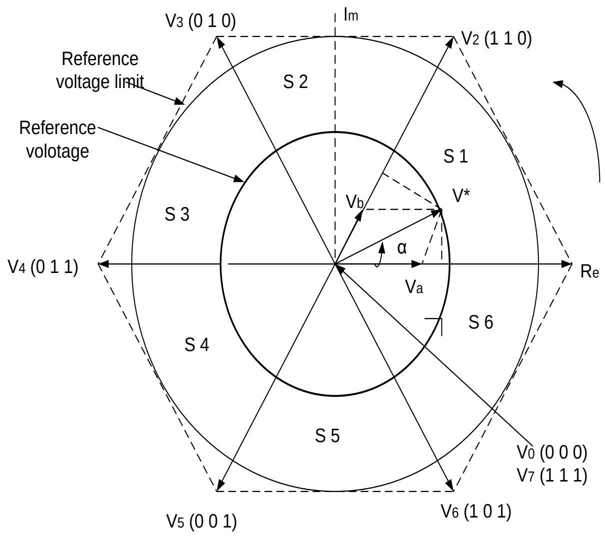

Fig. 7. Phase voltage space vector

The objective of space vector PWM technique is to approximate the reference voltage vector V^* using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period, T to be the same as that of V^* in the same period. The objective of Space Vector switching is to appropriate the sinusoidal line modulating signal (reference voltage vector) V^*, with the eight space vector (Vn, n = 0,1,…7). These eight space vectors form a hexagon Fig.7 which can be seen as consisting of six sector spanning 60° each.

The time of application of active space voltage vectors is found from Fig. 8 as:

$$T_1 = T_z \frac{V^*}{v_a} \frac{\sin(\pi/3-\alpha)}{\sin(2\pi/3)} \quad \text{----- (5)}$$

$$T_1 = T_z \frac{V^*}{v_b} \frac{\sin(\alpha)}{\sin(\pi/3)} \quad \text{----- (6)}$$

$$T_0 = T_z - (T_1 + T_2) \quad \text{----- (7)}$$

Where. $v_a = v_b = 2V_{dc}/3$.

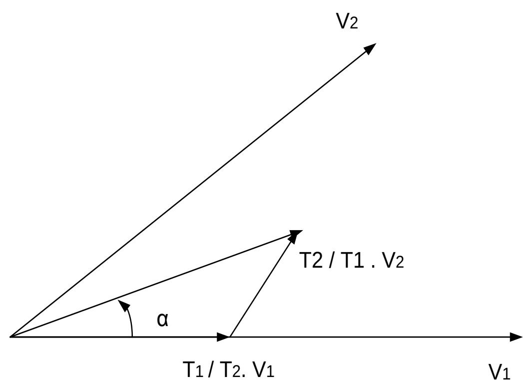

Fig. 8. Reference vector as a combination of adjacent vectors at sector 1.

In order to obtain fixed switching frequency and optimum harmonic performance from SVPWM, each leg should change its state only once in one switching period. This is achieved by applying zero state vectors followed by two adjacent active state vectors in half switching period. The next half of the switching period is the mirror image of the first half. The switching pattern for sector -1 is shown in fig.9.

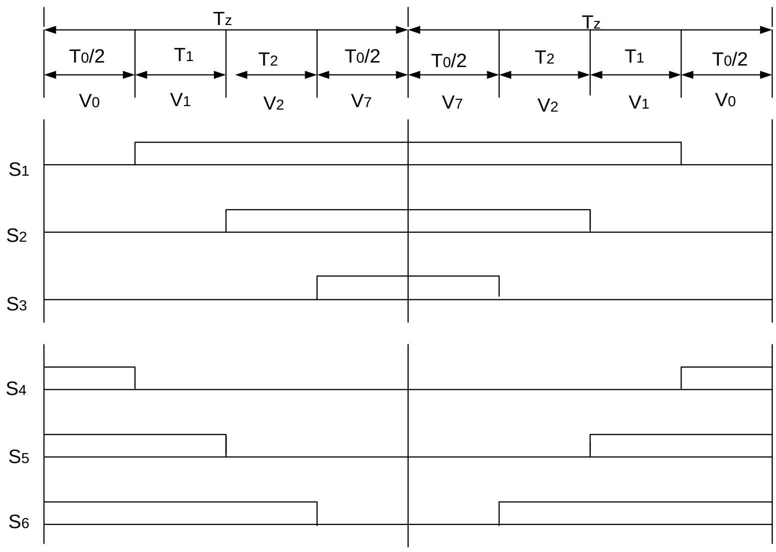

Fig.9. Switching pattern for sector I

IV. INTERPRETATION RESULTS

To study the performance of the SVPWM-DTC with direct torque control strategy, the simulation of the system was conducted using SIMULINK as in fig.10. Simulation results for a DTC system when controlling the 3-phase induction machine having parameter as in appendix-I are shown in fig.11 and fig.12 for both method.

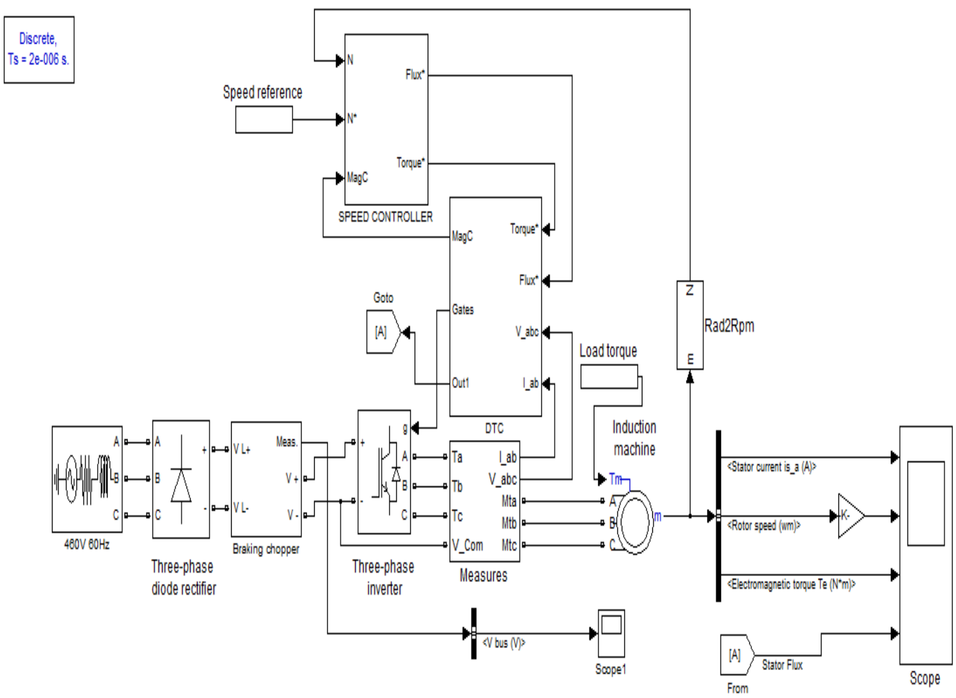

Fig. 10. Simulink model of SVM-DTC control

V. CONCLUSION

In this paper a SVPWM-DTC of induction machine have been proposed. An improved torque response was achieved with the SVPWM-DTC than the conventional DTC. The main improvements shown are reduction of torque ripples in transient and steady state response.

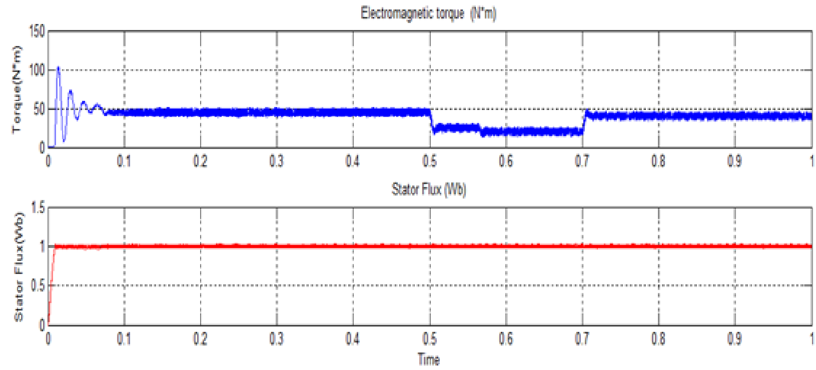

Fig. 11. Simulation results of classical DTC; a 20 N-m load is applied at 0.5 sec and 40 N-m at 0.7sec.

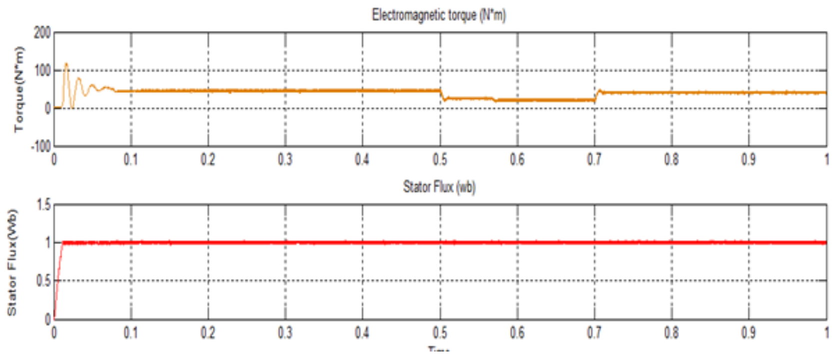

Fig. 12. Simulation results of SVPWM_ DTC; a 20 N-m load is applied at0.5 sec and 40 N-m at 0.7 sec.

APPENDIX-I

Motor rating and parameters

Motor rating	7.5kW
Load torque	20 N-m.
Speed	1800 r.p.m.
Pole pair	2
Stator resistance	0.6837 Ohm
Stator leakage inductance	0.004152 H
Rotor leakage inductance	0.004152H
Mutual inductance	0.1486 H
Moment of inertia J	0.05Kg.m^2

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