Analysis of Direct Torque Controller Based on Space Vector Modulation with Adaptive Stator Flux Observer for Induction Motor Application

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Abstract— This paper describes a combination of direct torque control (DTC) and space vector modulation (SVM) for an adjustable speed sensor less induction motor (IM) drive. The motor drive is supplied by a two-level SVPWM inverter. The inverter reference voltage is obtained based on input-output feedback linearization control, using the IM model in the stator D–Q axes reference frame with stator current and flux vectors components as state variables. Moreover, a robust full-order adaptive stator flux observer is designed for a speed sensor less DTC-SVM system and a new speed-adaptive law is given. By designing the observer gain matrix based on state feedback H∞ control theory, the stability and robustness of the observer systems are ensured. The stability of the speed adaptive stator flux observer is also guaranteed by the gain matrix in very low speed finally, the effectiveness and validity of the proposed control approach are verified by simulation results. Here we use MATLAB/Simulink for the simulation purpose, the proposed control algorithms are verified by extensive simulation results.

Keywords— Direct Torque Control, Field oriented control, space vector modulation, Torque and flux control

I. INTRODUCTION

Direct Torque Control (DTC) abandons the stator current control philosophy, characteristic of field oriented control (FOC) and achieves bang-bang torque and flux control by directly modifying the stator voltage in accordance with the torque and flux errors [1]. So, it presents a good tracking for both electromagnetic torque and stator flux. DTC is characterized by the fast dynamic response, structural simplicity, and strong robustness in the face of parameter uncertainties and perturbations. One of the disadvantages of conventional DTC is high torque ripple. Several techniques have been developed to reduce the torque ripple. One of them is duty ratio control method.

Industry ratio control, a selected output voltage vector is applied to a portion of one sampling period, and a zero voltage vector is applied for the rest of the period. The pulse duration of output voltage vector can be determined by a fuzzy logic controller. In torque-ripple minimum condition during one sampling period is obtained from instantaneous torque variation equations [2]. The pulse duration of output voltage vector is determined by the torque-ripple minimum condition. These improvements an greatly reduce the torque ripple, but they increase the complexity of DTC algorithm. An alternative method to reduce the ripples is based on space vector modulation (SVM) technique.

Direct torque control based on space vector modulation (DTC-SVM) preserve DTC transient merits, furthermore, produce better quality steady-state performance in a wide speed range. At each cycle period, SVM technique is used to obtain the reference voltage space vector to exactly compensate the flux and torque errors. The torque ripple of DTC-SVM in low speed can be significantly improved.

In this paper, SVM-DTC technique based on input-output linearization control scheme for induction machine drives is developed. Furthermore, a robust full-order speed adaptive stator flux observer is designed for a speed sensor less DTC-SVM system and a speed-adaptive law is given [3]. The observer gain matrix, which is obtained by solving linear matrix inequality, can improve the robustness of the adaptive observer gain.

The stability of the speed adaptive stator flux observer is also guaranteed by the gain matrix in very low speed. The proposed control algorithms are verified by extensive simulation results.

II. DIRECT TORQUE CONTROL (DTC)

Direct Torque Control (DTC) is a method that has emerged to become one possible alternative to the well-known Vector Control of Induction Motors. This method provides a good performance with a simpler structure and control diagram [4]. In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate VSI state. The main advantages offered by DTC are:

- Decoupled control of torque and stator flux.
- Excellent torque dynamics with minimal response time.
- Inherent motion-sensor less control method since the motor speed is not required to achieve the torque control.

- ➢ The absence of coordinate transformation (required in Field Oriented Control (FOC)).
- ➢ The absence of voltage modulator, as well as other controllers such as PID and current controllers (used in FOC).
- ➢ Robustness for rotor parameters variation. Only the stator resistance is needed for the torque and stator flux estimator.

These merits are counterbalanced by some drawbacks:

- ➢ Possible problems during starting and low-speed operation and during changes in torque command. The requirement of torque and flux estimators, implying the consequent parameters identification (the same as for other vector controls).
- ➢ Variable switching frequency caused by the hysteresis controllers employed.
- ➢ Inherent torque and stator flux ripples.
- ➢ Flux and current distortion caused by sector changes of the flux position.
- ➢ Higher harmonic distortion of the stator voltage and current waveforms compared to other methods such as FOC.
- ➢ Acoustical noise produced due to the variable switching frequency. This noise can be particularly high during low-speed operation.

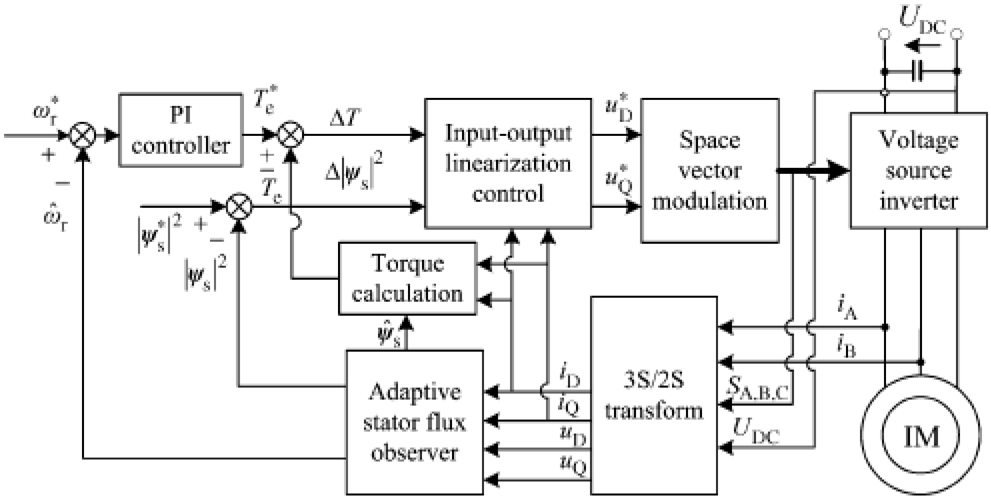

Fig. 1 Block diagram of the DTC-SVM system.

A variety of techniques has been proposed to overcome some of the drawbacks present in DTC. Some solutions proposed are DTC with Space Vector Modulation (SVM); the use of a duty--ratio controller to introduce a modulation between active vectors chosen from the look-up table and the zero vectors; use of artificial intelligence techniques, such as Neuro-Fuzzy controllers with SVM [5]. These methods achieve some improvements such as torque ripple reduction and fixed to switch frequency operation. However, the complexity of the control is considerably increased.

A different approach to improving DTC features is to employ different converter topologies from the standard two-level VSI. Some authors have presented different implementations of DTC for the three-level Neutral Point Clamped (NPC) VSI. This work will present a new control scheme based on DTC designed to be applied to an Induction Motor fed with a three-level VSI.

The major advantage of the three-level VSI topology when applied to DTC is the increase in the number of voltage vectors available. This means the number of possibilities in the vector selection process is greatly increased and may lead to a more accurate control system, which may result in a reduction in the torque and flux ripples [6]. This is of course achieved, at the expense of an increase in the complexity of the vector selection process.

To understand the answer to this question we have to understand that the basic function of a variable speed drive (VSD) is to control the flow of energy from the mains to the process. Energy is supplied to the process through the motor shaft. Two physical quantities describe the state of the shaft: torque and speed [7]. To control the flow of energy we must, therefore, ultimately, control these quantities. In practice, either one of them is controlled or we speak of “torque control” or “speed control”. When the VSD operates in torque control mode, the speed is determined by the load. Likewise, when operated in speed control, the torque is determined by the load. Initially, DC motors were used as VSDs because they could easily achieve the required speed and torque without the need for sophisticated electronics. However, the evolution of AC variable speed drive technology has been driven partly by the desire to emulate the excellent performance of the DC motor, such as fast torque response and speed accuracy, while using rugged, inexpensive and maintenance free AC motors.

III. SPACE VECTOR PWM THEORY

The Space Vector PWM generation module accepts modulation index commands and generates the appropriate gate drive waveforms for each PWM cycle. This section describes the operation and configuration of the SVPWM module.

A three-phase 2-level inverter with dc link configuration can have eight possible switching states, which generates an output voltage of the inverter. Each inverter switching state generates a voltage Space Vector (V1 to V6 active vectors, V7 and V8 zero voltage vectors) in the Space Vector plane [8]. The magnitude of each active vector (V1to V6) is 2/3 Vdc (dc bus voltage).

The Space Vector PWM (SVPWM) module inputs modulation index commands (U_Alpha and U_Beta) which are orthogonal signals (Alpha and Beta) as shown in Fig.2. The gain characteristic of the SVPWM module is given in Fig. 3. The vertical axis of

Figure represents the normalized peak motor phase voltage (V/V_{dc}) and the horizontal axis represents the normalized modulation index (M).
The inverter fundamental line-to-line RMS output voltage (V_{line}) can be approximated (linear range) by the following equation:

$$Vline = Umag * Mod\_Scl * \frac{\frac{V_{dc}}{\sqrt{6}}}{2^{25}} \quad (1)$$

Where dc bus voltage (V_{dc}) is in volts

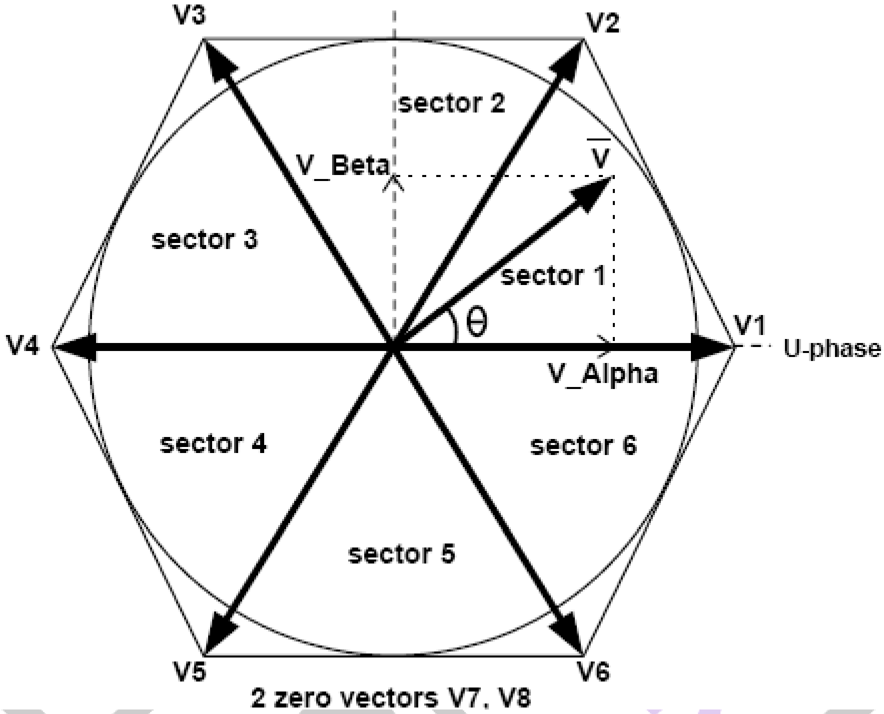

Fig. 2 Space Vector Diagram

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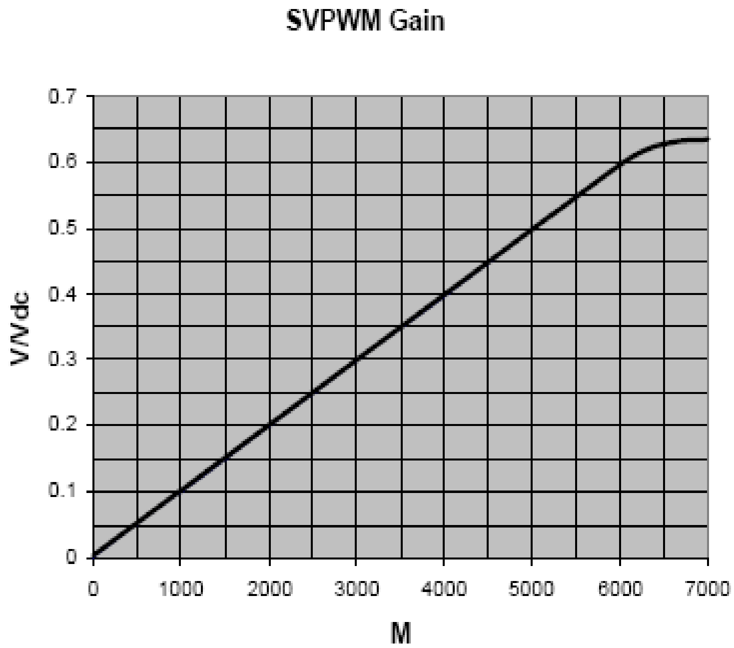

Fig. 3 Transfer Characteristics

The maximum achievable modulation (Umag_L) in the linear operating range is given by:

$$Umag\_L = 2^{25} * \frac{\sqrt{3}}{Mod\_Scl} \quad (2)$$

Over modulation occurs when modulation Umag > Umag_L. This corresponds to the condition where the voltage vector in (Figure: voltage vector rescaling)increases beyond the hexagon boundary [9]. Under such circumstance, the Space Vector PWM algorithm will rescale the magnitude of the voltage vector to fit within the Hexagon limit. The magnitude of the voltage vector is restricted within the Hexagon; however, the phase angle (θ) is always preserved. The transfer gain (Figure: transfer characteristics) of the PWM modulator reduces and becomes non-linear in the overmodulation region.

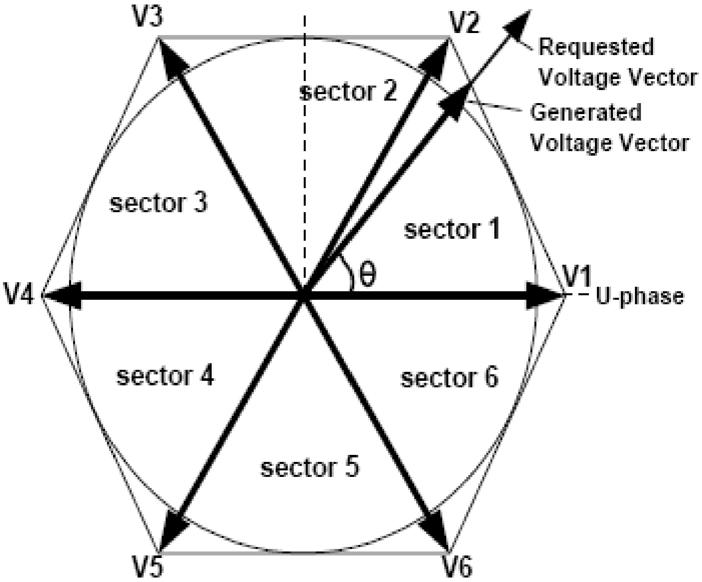

Fig. 4 Voltage Vector Rescaling

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IV. SVM PWM TECHNIQUE

The Pulse Width modulation technique permits to obtain three phase system voltages, which can be applied to the controlled output. Space Vector Modulation (SVM) principle differs from other PWM processes in the fact that all three drive signals for the inverter will be created simultaneously [10]. The implementation of SVM process in digital systems necessitates less operation time and also less program memory.

The SVM algorithm is based on the principle of the space vector u*, which describes all three output voltages ua, ub and uc :

$$u^* = \frac{2}{3}\left(ua + ub + a2.uc\right) \qquad (3)$$

Where a = -1/2 + j . v3/2 We can distinguish six sectors limited by eight discrete vectors u0…u7 (fig: - inverter output voltage space vector), which correspond to the 23 = 8 possible switching states of the power switches of the inverter.

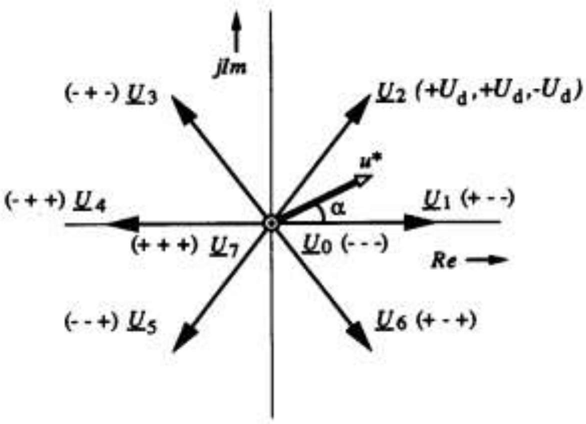

Fig. 5 Space vector Modulation

The amplitude of u0 and u7 equals 0. The other vectors u1…u6 have the same amplitude and are 60 degrees shifted.

By varying the relative on-switching time Tc of the different vectors, the space vector u* and also the output voltages ua, ub and uc can be varied and is defined as:

ua = Re (u*)

ub = Re (u* . a-1)

$uc = Re (u^* . a-2)$ (4)

During a switching period Tc and considering for example the first sector, the vectors u0, u1 and u2 will be switched on alternatively.

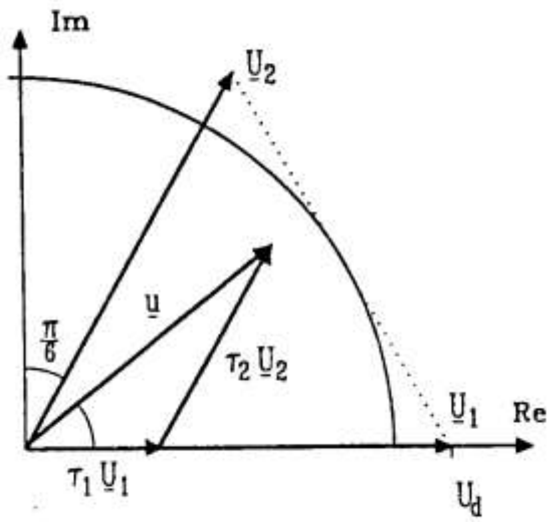

Fig. 6 Definition of the Space vector

Depending on the switching times t0, t1 and t2 the space vector u* is defined as:

$u^* = 1/Tc . (t0 . u0 + t1 . u1 + t2 . u2)$

$u^* = t0 . u0 + t1 . u1 + t2 . u2$

$u^* = t1 . u1 + t2 . u2$ (5)

Where

$t0 + t1 + t2 = Tc$ and

$t0 + t1 + t2 = 1$

t0, t1 and t2 are the relative values of the on switching times.

They are defined as: $t1 = m . \cos (a + p/6)$

$t2 = m . \sin a$

$t0 = 1 - t1 - t2$

Their values are implemented in a table for a modulation factor m = 1. Then it will be easy to calculate the space vector u* and the output voltages ua, ub and uc. The voltage vector u* can be provided directly by the optimal vector control laws w1, v_{sa} and v_{sb}. In order to generate the phase voltages ua, ub and uc corresponding to the desired voltage vector u* the following SVM strategy is proposed.

V. SIMULATION RESULTS AND DISCUSSION

In order to understand the performance of an adjustable speed sensor less induction motor (IM) drive a combination of direct torque control (DTC) and space vector modulation (SVM) is considered as shown in Fig. The performance of the induction motor with conventional direct torque control as shown in Fig. 8 to Fig. 11 and with direct torque control based on SVM are shown in Fig. 13 to Fig. 16.

CASE I: conventional direct torque control

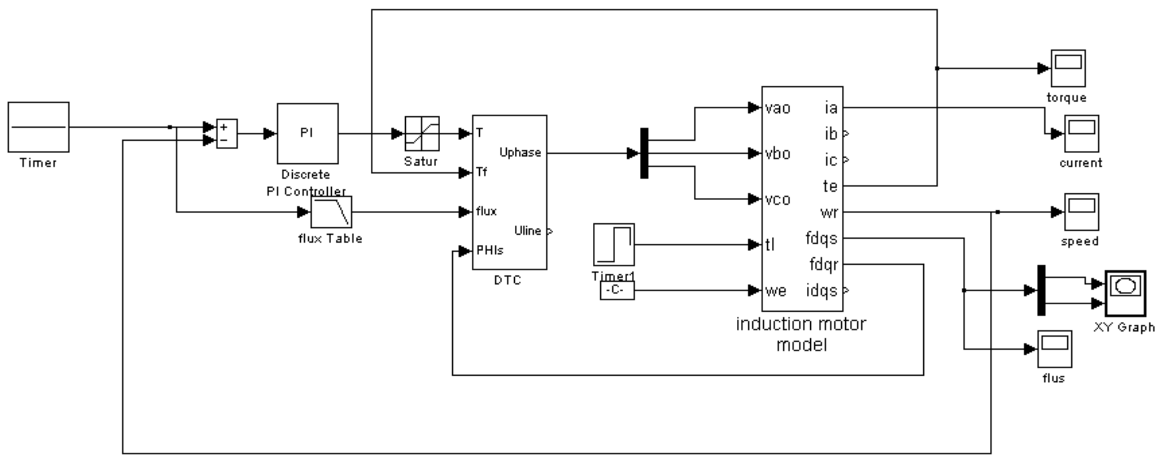

Fig. 7 Simulation diagram of induction motor drive with conventional direct torque control

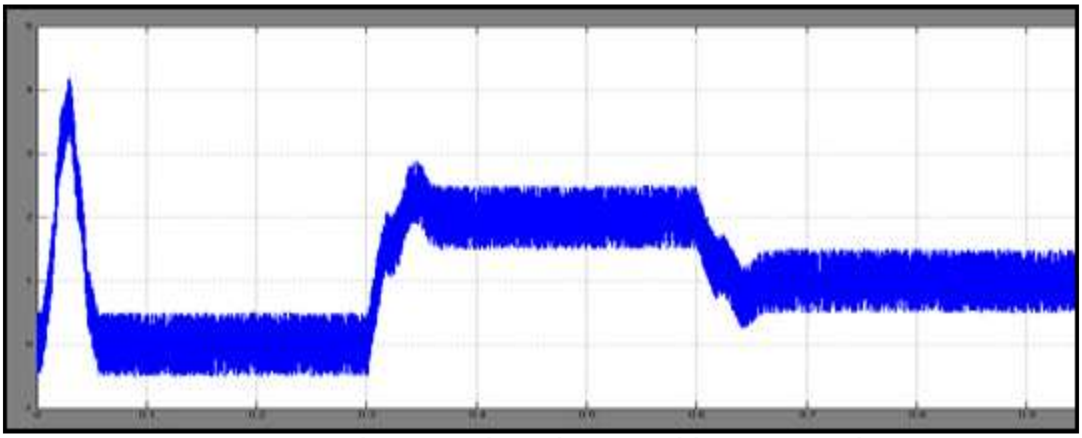

Fig. 8 Torque induction motor drive with conventional direct torque control

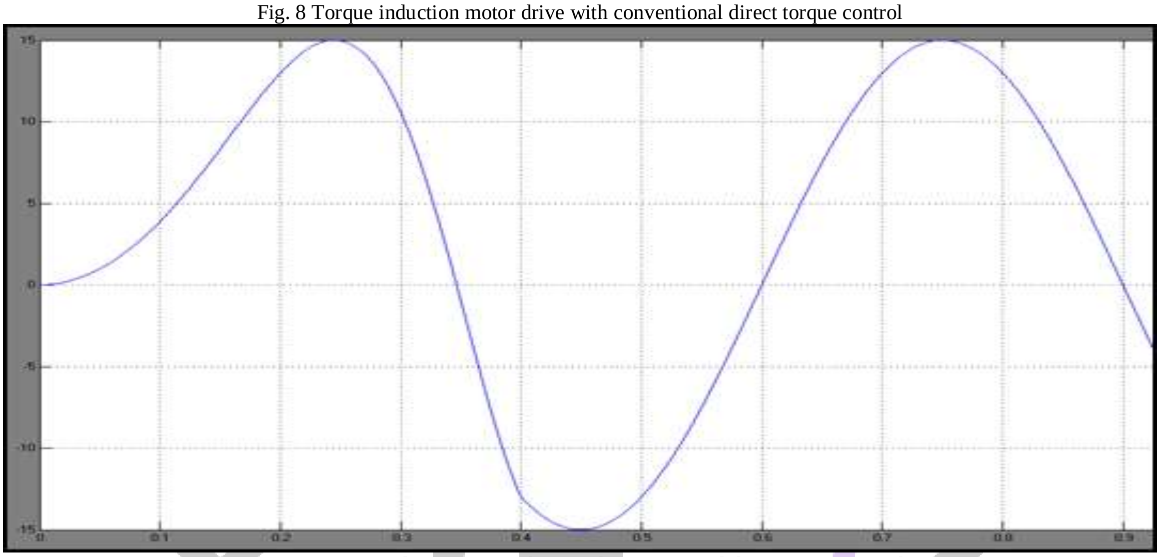

Fig. 9 Current induction motor drive with conventional direct torque control

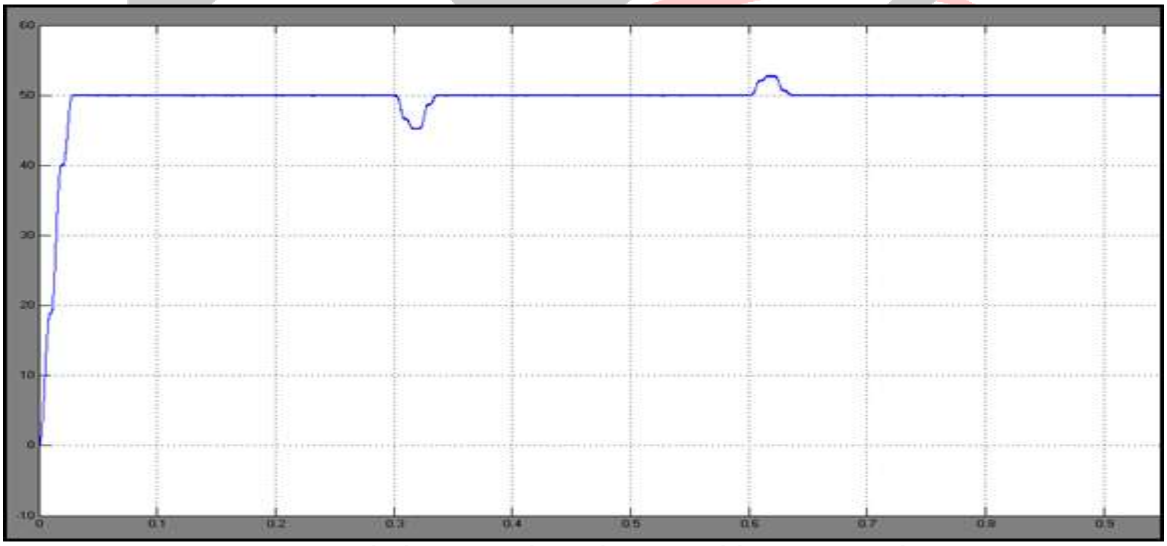

Fig. 10 Speed induction motor drive with conventional direct torque control

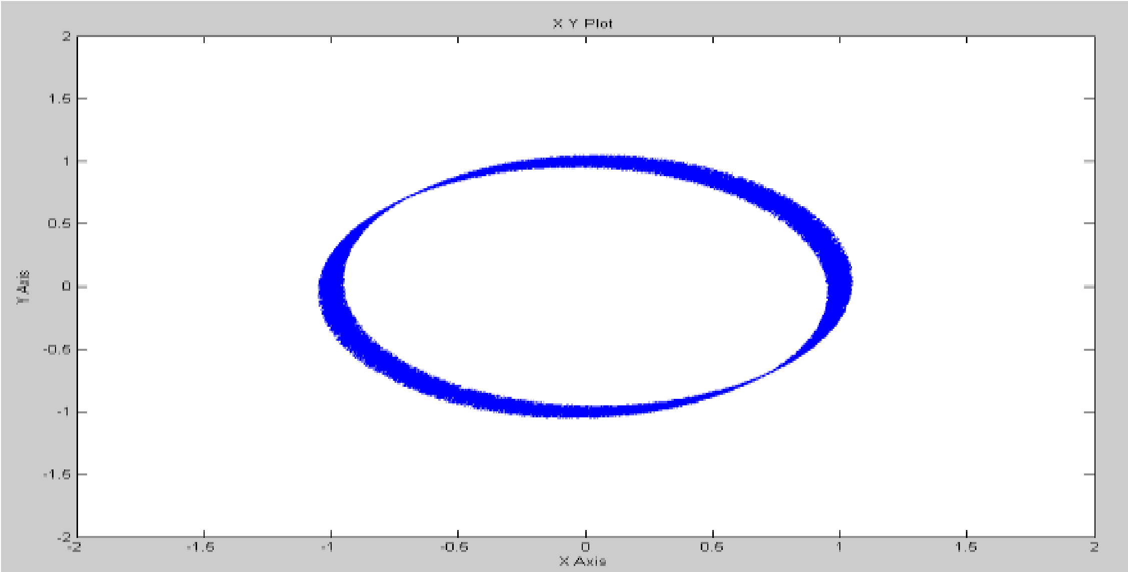

Fig. 11 XY GRAPH induction motor drive with conventional direct torque control

CASE II: direct torque control based on SVM

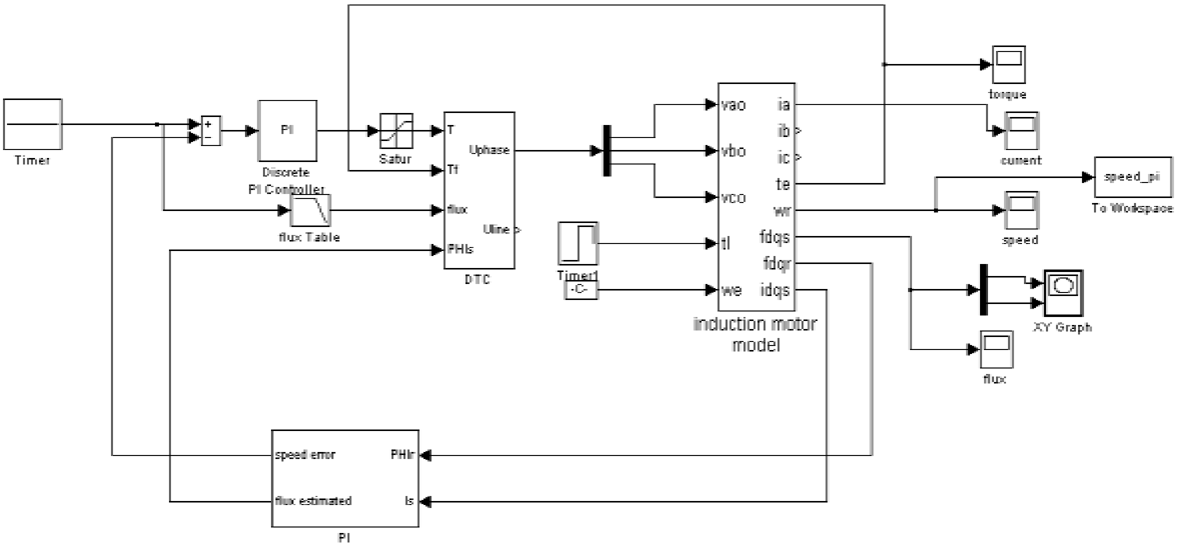

Fig. 12 Simulation diagram of induction motor drive with direct torque control based on SVM

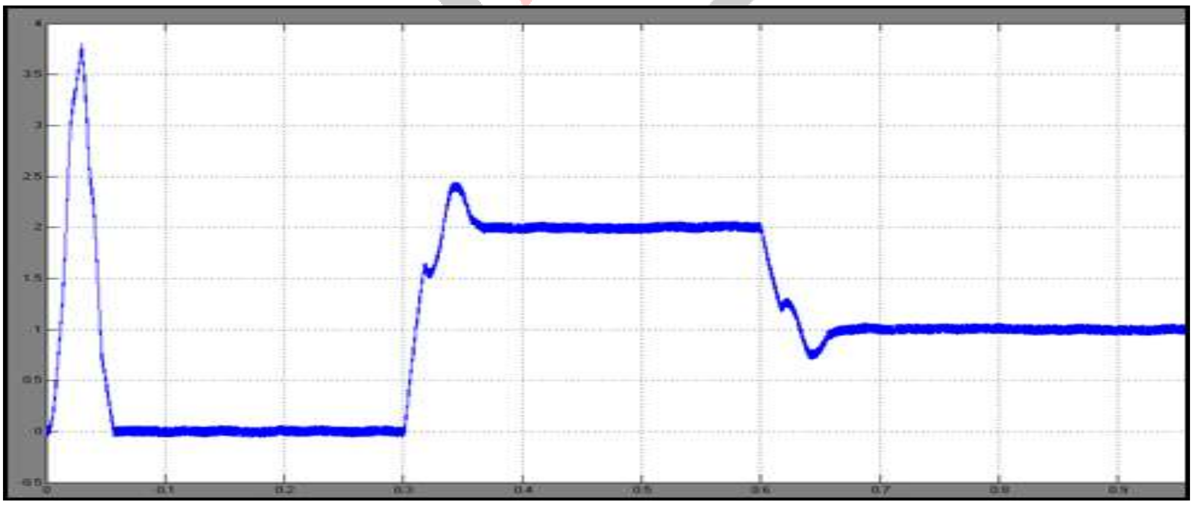

Fig. 13 Torque induction motor drive with direct torque control based on SVM


Fig. 14 Current induction motor drive with direct torque control based on SVM

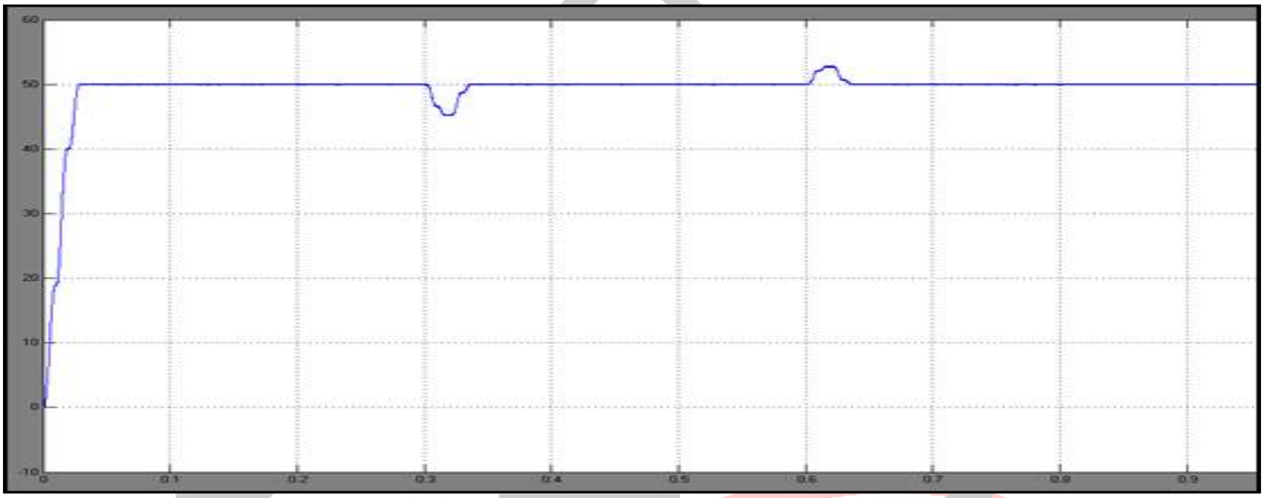
Fig. 15 Speed induction motor drive with direct torque control based on SVM

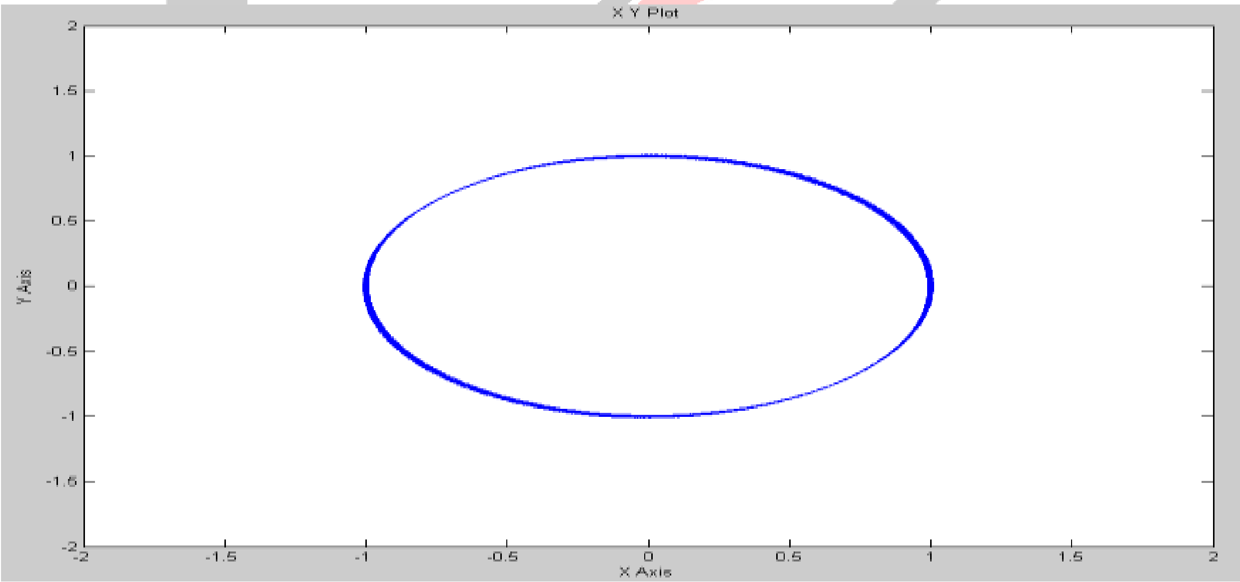

Fig. 16 XY graph induction motor drive with direct torque control based on SVM

VI. CONCLUSION

A novel DTC-SVM scheme has been developed for the IM drive system, which is on the basis of input-output linearization control. In this control method, an SVPWM inverter is used to feed the motor, the stator voltage vector is obtained to fully compensate the stator flux and torque errors. Furthermore, a robust full-order adaptive flux observer is designed for a speed sensor less DTC-SVM system. The stator flux and speed are estimated synchronously. By designing the constant observer gain matrix based on state feedback control theory, the robustness and stability of the observer systems are ensured. Therefore, the proposed sensor less drive system is capable of steadily working in very low speed, has much smaller torque ripple and exhibits good dynamic and steady-state performance.

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