Middle-East Journal of Scientific Research
24 (Recent Innovations in Engineering, Technology, Management & Applications): 95-103, 2016
ISSN 1990-9233; © IDOSI Publications, 2016
DOI: 10.5829/idosi.mejsr.2016.24.RIETMA116

Implementation of Direct Torque Controlled Space Vector Modulation Fed Induction Motor Drive

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Abstract: The fundamental idea of direct torque control of induction machines is investigated in order to emphasize the property produced by a given voltage vector on stator flux and torque variations. The proposed control system is based on Space Vector Modulation (SVM) of electrical machines, Improvement model reference adaptive system and real time of stator resistance and estimation of stator flux. The purpose of this control is to minimize electromagnetic torque and flux ripple and minimizing distortion of stator current. In this proposed method, PI torque and PI flux controller are designed to achieve estimated torque and flux with good tracking and fast response with reference torque and there is no steady state error. In addition, design of PI torque and PI flux controller are used to optimize voltages in d-q reference frame that applied to SVM. The simulation Results of proposed DTC-SVM have complete excellent performance in steady and transient states as compared with classical DTC-SVM.

Key words: Direct torque control · Induction motor · PI controller · Space vector modulation

INTRODUCTION

Induction motors are used to generate the torque required in many industries and motor control applications. The squirrel cage induction motor has been widely used in such applications due to its ruggedness, low maintenance cost and high power rating [1, 2]. Adjustable Speed Drives (ADS) are gene rally used in industry. In most drives AC motors are applied. The standard in those drives are Induction Motors (IM) and recently also Permanent Magnet Synchronous Motors (PMSM) are offered. Variable speed drives are widely used in application such as pumps, fans, elevators, electrical vehicles, heating, ventilation and air-conditioning (HVAC), robotics, wind generation systems, ship propulsion, etc. Previously, DC machines were preferred for variable speed drives. However, DC motors have disadvantages of higher cost, higher rotor inertia and maintenance problem with commutators and brushes. In addition they cannot operate in dirty and explosive environments. The AC motors do not have the Disadvantages of DC machines. Therefore, in last three decades the DC motors are progressively replaced by AC drives. The responsible for those result are development of modern semiconductor devices, especially power Insulated Gate Bipolar Transistor (IGBT) and Digital Signal Processor (DSP) technologies. The most economical IM speed control methods are realized by using frequency converters. Many different topologies of frequency converters are proposed and investigated in a literature. However, a converter consisting of a diode rectifier, a dc-link and a Pulse Width Modulated (PWM) voltage inverter is most commonly used in industrial applications [3, 4]. The high-performance frequency controlled PWM inverter - fed IM drive should be characterized by:

- Fast flux and torque response,
- Available maximum output torque in wide range of speed operation region,
- Constant switching frequency,
- Uni-polar voltage PWM,
- Low flux and torque ripple,
- Robustness for parameter variation,
- Four-quadrant operation

These features depend on the applied control strategy. The main goal of the chosen control method is to provide the best possible parameters of drive. Additionally, a very important requirement regarding control method is simplicity (simple algorithm, simple Tuning and operation with small controller dimension leads to low price of final product).

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Using Newton's second law to relate Ft to the tangential acceleration a_t = ra, where a is the angular acceleration:

$F_t = ma_t = mra$

A general classification of the variable frequency IM control methods is presented in Fig. 1.1. These methods can be divided into two groups: scalar and vector.

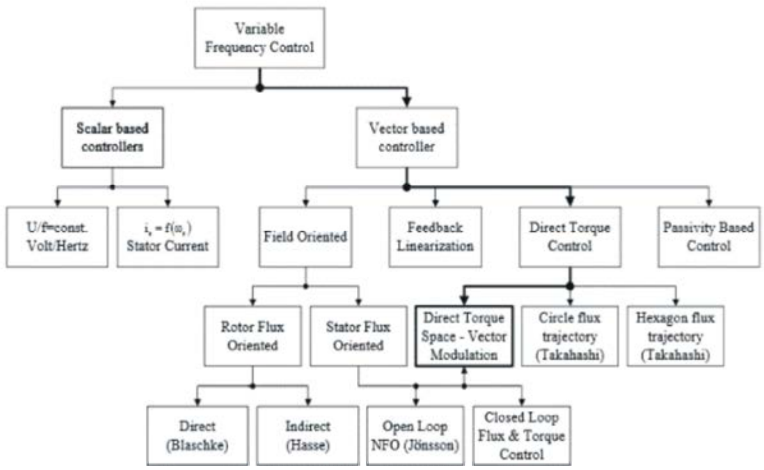

Fig. l: General Classification of induction motor control methods

The scalar control methods are simple to implement. The most popular in industry is constant Voltage/ Frequency (V/Hz=const.) control. This is the simplest, which does not provide a high-performance. The vector control group allows not only control of the voltage amplitude and frequency, like in the scalar control methods, but also the instantaneous position of the voltage, current and flux vectors. This improves significantly the dynamic behavior of the drive. However, induction motor has a nonlinear structure and a coupling exists in the motor, between flux and the produced electromagnetic torque. Therefore, several methods for decoupling torque and flux have been proposed. These algorithms are based on different ideas and analysis.

Unknown mass will try to rotate the meter stick counter clockwise and known mass will try to rotate the meter stick clockwise.

Counter clockwise torque = Unknown mass X Lever-Arm-1
Clockwise torque = Known mass X Lever- Arm-2
For balance, counter clockwise torque must equal the clockwise torque.
Unknown mass X Lever-Arm-1 = Known mass X Lever-Arm-2
Unknown mass = [Known mass X Lever- Arm-2] ^ [Lever-Arm-1]

The first vector control method of induction motor was Field Oriented Control (FOC) presented by K. Hasse (Indirect FOC) and F. Blaschke (Direct FOC) in early of 70s. Those methods were investigated and discussed by many researchers and have now become an industry standard. In this method the motor equations are transformed into a coordinate system that rotates in synchronism with the rotor flux vector. The FOC method guarantees flux and torque decoupling. However, the induction motor equations are still nonlinear fully decoupled only for constant flux operation. An other method known as Feedback Linearization Control (FLC) introduces a new nonlinear transformation of the IM state variables, so that in the new coordinates, the speed and rotor flux amplitude are decoupled by feedback. A method based on the variation theory and energy shaping has been investigated recently and is called Passivity Based Control (PBC). In this case the induction motor is described in terms of the Euler-L arrange equations expressed in generalized coordinates. In the middle of 80s new strategies for the torque control of induction motor was presented by I. Takahashi and T. Noguchi as Direct Torque Control (DTC) and by M. Depenbrock as Direct Self Control (DSC). Those methods thanks to the other approach to control of IM have become alternatives for the classical vector control - FOC. The authors of the new control strategies proposed to replace motor decoupling and linearization via coordinate transformation, like in FOC, by hysteresis controllers, which corresponds very well to on-off operation of the inverter semiconductor power devices. These methods are referred to as classical DTC. Since 1985 they have been continuously developed and improved by many researchers. Simple structure and very good dynamic behavior are main features of DTC. However, classical DTC has several disadvantages, from which most important is variable switching frequency. Recently, from the classical DTC methods a new control techniques called Direct Torque Control - Space Vector Modulated (DTC- SVM) has been developed. In this new method disadvantages of the classical DTC are eliminated. Basically, the DTC-SVM strategies are the methods, which operates with constant switching frequency. These methods are the main subject of this thesis. The DTC-SVM structures are based on the same fundamentals and analysis of the drive as classical DTC. However, from the formal considerations these methods can also be viewed as stator field oriented control (SFOC), as shown in Fig. Presented DTC- SVM technique has also simple structure and provide dynamic behavior comparable with classical DTC. However, DTC-SVM method is characterized by much better parameters in steady state operation. Therefore, the following paper can be formulated: "The most convenient industrial control scheme for voltage source inverter-fed induction motor drives is direct torque control with space vector modulation DTC-SVM" In order to prove the above thesis the author used an analytical and simulation based approach, as well as experimental verification on the laboratory setup with 5 kVA and 18 kVA IGBT inverters with 3 kW and 15 kW induction motors, respectively. Moreover, the control algorithm DTC- SVM has been introduced used in a serial commercial product of Polish manufacture TWERD, Torun. In the author's opinion the following parts of the thesis are his original achievements:

- Elaboration and experimental verification of flux and torque controller design for DTC- SVM induction motor drives,
- Development of a SABER - based simulation algorithm for control and investigation voltage source inverter-fed induction motors,
- Construction and practical verification of the experimental setups with 5 kVA and 18 kVA IGBT inverters,
- Bringing into production and testing of developed DTC-SVM algorithm in Polish industry.

Voltage Source Inverter Fed Induction Motor Drive: When describing a three-phase IM by a system of equations following simplifying assumptions are made: The three-phase motor is symmetrical, only the fundamental harmonic is considered, while the higher harmonics of the spatial field distribution and of the magneto motive force (MMF) in the air gap are disregarded, the spatially distributed stator and rotor windings are replaced by a specially formed, so-called concentrated coil, the effects of anisotropy, magnetic saturation, iron losses and eddy currents are neglected, the coil resistances and reactance are taken to be constant, in many cases, especially when considering steady state, the current and voltages are taken to be sinusoidal.

The space vector method is generally used to describe the model of the induction motor. The advantages of this method are as follows: reduction of the number of dynamic equations, possibility of analysis at any supply voltage waveform, the equations can be represented in various rectangular coordinate systems. A three-phase symmetric system represented in a neutral coordinate system by phase quantities, such as: voltages, currents or flux linkages, can be replaced by one resulting space vector of, respectively, voltage, current and flux-linkage.

Voltage Source Inverter: The three-phase two level VSI consists of six active switches. The basic topology of the inverter is shown in Fig. The converter consists of the three legs with IGBT transistors, or (in the case of high power) GTO thyristors and free-wheeling diodes. The inverter is supplied by a voltage source composed of a diode rectifier with a C filter in the dc-link. The capacitor C is typically large enough to obtain adequately low voltage source impedance for the alternating current component in the dc-link.

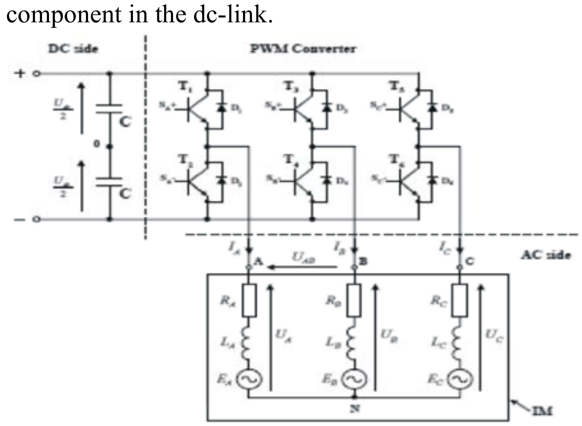

Fig. 2: Topology of the voltage source inverter

The voltage source inverter makes it possible to connect each of the three motor phase coils to a positive or negative voltage of the dc link. Fig. explains the fabrication of the output voltage waves in square-wave, or six-step, mode of operation. The phase voltages are related to the dc-link center point. 0.

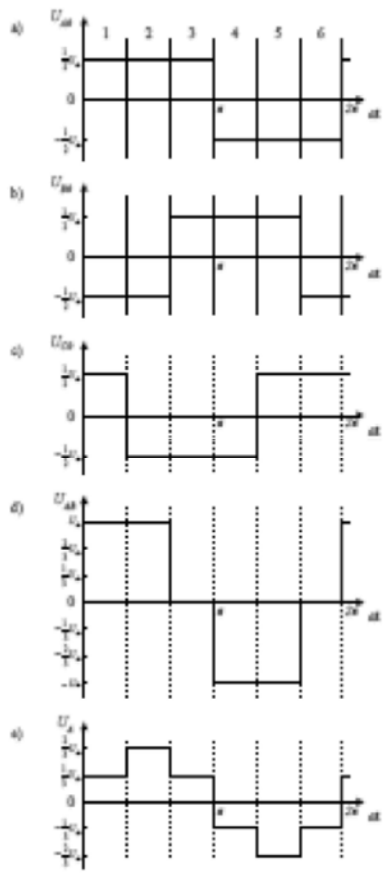

Fig. 3: The output voltage waveforms in six-step mode

Pulse Width Modulation: In the voltage source inverter conversion of dc power to three-phase ac power is performed in the switched mode. This mode consists in power semiconductors switches are controlled in an on-off fashion. The actual power flow in each motor phase is controlled by the duty cycle of the respective switches. To obtain a suitable duty cycle for each switches technique pulse width modulation is used. Many different modulation methods were proposed and development of it is still in progress. The modulation method is an important part of the control structure. It should provide features like: wide range of linear operation, low content of higher harmonics in voltage and current, low frequency harmonics, operation in over modulation, reduction of common mode voltage and minimal number of switching to decrease switching losses in the power components.

The development of modulation methods may improve converter parameters. In the carrier based PWM methods the Zero Sequence Signals (ZSS) are added to extend the linear operation range the carrier based modulation methods with ZSS correspond to space vector modulation. All PWM methods have specific features. However, there is not just one PWM method which satisfies all requirements in the whole operating region. Therefore, in the literature are proposed modulators, which contain from several modulation methods. For example, adaptive space vector modulation, which provides the following features: full control range including over modulation and six-step mode, achieved by the use of three different modulation algorithms, reduction of switching losses thanks to an instantaneous tracking peak value of the phase current.

The content of the higher harmonics voltage (current) and electromagnetic interference generated in the inverter fed drive depends on the modulation technique. Therefore, PWM methods are investigated from this point of view. To reduce these disadvantages several methods have been proposed. One of these methods is random modulation (RPWM). The classical carrier based method or space vector modulation method are named deterministic (DEPWM), because these methods work with constant switching frequency. In opposite to the deterministic methods, the random modulation methods work with variable frequency, or with randomly changed switching sequence.

The most widely used method of pulse width modulation are carrier based. This method is also known as the sinusoidal (SPWM), triangulation, sub- harmonic, or sub-oscillation method.

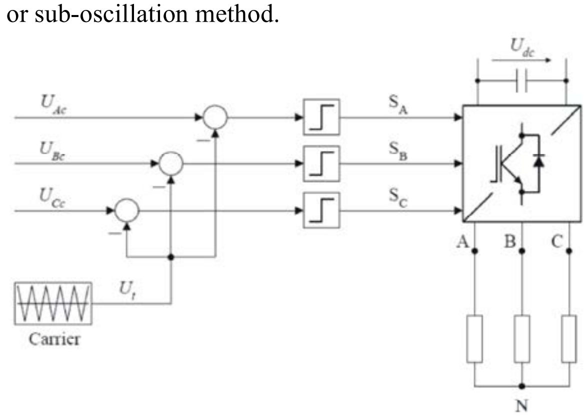

Fig. 4: Block scheme of carrier based sinusoidal PWM

Sinusoidal modulation is based on triangular carrier signal as shown in Fig. In this method three reference signals UAc, UBc, UCc are compared with triangular carrier signal Ut, which is common to all three phases.

In this way the logical signals SA, SB, SC are generated, which define the switching instants of the power transistors.

Vector Control Methods of Induction Motor VI: The direct torque control (DTC) method creates a base for further analyse of DTC-SVM algorithms. The principle of the field oriented control (FOC) is based on an analogy to the separately excited dc motor. In this motor flux and torque can be controlled independently. The control algorithm can be implemented using simple regulators, e.g. PI- regulators.

In induction motor independent control of flux and torque is possible in the case of coordinate system is connected with rotor flux vector. A coordinate system d - q is rotating with the angular speed equal to rotor flux vector angular speed K sr Q = £1, which is defined as follows:

$$\Omega_{sr} = \frac{d\gamma_{sr}}{dt}$$

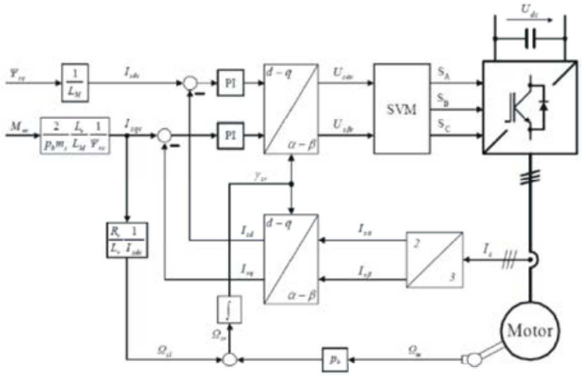

Fig. 5: Block diagram of the Indirect Field Oriented Control (IFOC)

The property of the FOC methods can be summarized as follows: The method is based on the analogy to control of a DC motor, FOC method does not guarantee an exact decoupling of the torque and flux control in dynamic and steady state operation, relationship between regulated value and control variables is linear only for constant rotor flux amplitude, full information about motor state variable and load torque is required (the method is very sensitive to rotor time constant), current controllers are required, coordinate transformations are required, a PWM algorithm is required (it guarantees constant switching frequency), in the DFOC rotor flux estimator is required, in the IFOC mechanical speed is required, the stator currents are sinusoidal except of high frequency switching harmonics.

The transformation of the induction motor equations in the field coordinates has a good physical basis because it corresponds to the decoupled torque production in a separately excited DC motor. However, from the theoretical point of view, other types of coordinates can be selected to achieve decoupling and linearization of the induction motor equations. In it is shown that a nonlinear dynamic model of IM can be considered as equivalent to two third-order decoupled linear systems. In a controller based on a multi-scalar motor model has been proposed. The new state variables have been chosen.

In result the motor speed is fully decoupled from the rotor flux. In the authors proposed a nonlinear transformation of the motor states variables, so that in the new coordinates, the speed and rotor flux amplitude are decoupled by feedback. Others proposed also modified methods based on Feedback Linearization Control.

The stator flux amplitude sc and the electromagnetic torque c M are the reference signals which are compared with the estimated s and e M" values respectively. The flux e and torque M e errors are delivered to the hysteresis controllers. The digitized output variables ^d, Md and the stator flux position sector (N) ss y selects the appropriate voltage vector from the switching table. Thus, the selection table generates pulses SA, SB, SC to control the power switches in the inverter.

Direct Flux and Torque Control with Space Vector Modulation (DTC-SVM): Direct flux and torque control with space vector modulation (DTC-SVM) schemes are proposed in order to improve the classical DTC. The DTC-SVM strategies operate at a constant switching frequency. In the control structures, space vector modulation (SVM) algorithm is used. The type of DTC-SVM strategy depends on the applied flux and torque control algorithm. Basically, the controllers calculate the required stator voltage vector and then it is realized by space vector modulation technique.

Different structures of DTC-SVM methods are presented in the next section. For each of the control structures, different controller design methods are proposed. The classical DTC algorithm is based on the instantaneous values and directly calculated the digital control signals for the inverter. The control algorithm in DTCSVM methods are based on averaged values whereas the switching signals for the inverter are calculated by space vector modulator. This is main difference between classical DTC and DTC-SVM control methods.

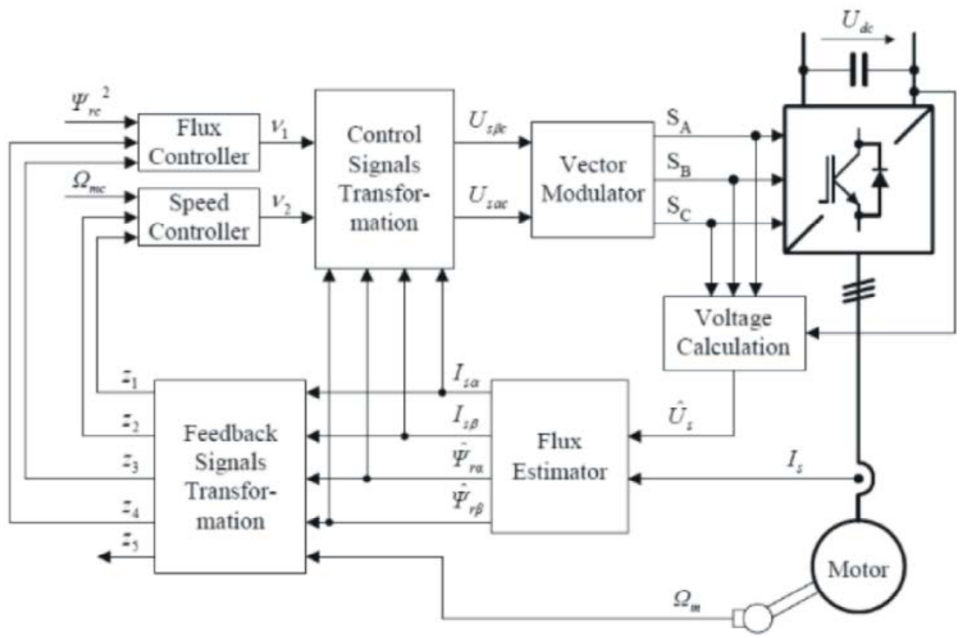

Fig. 6: Block scheme of the feedback linearization control method

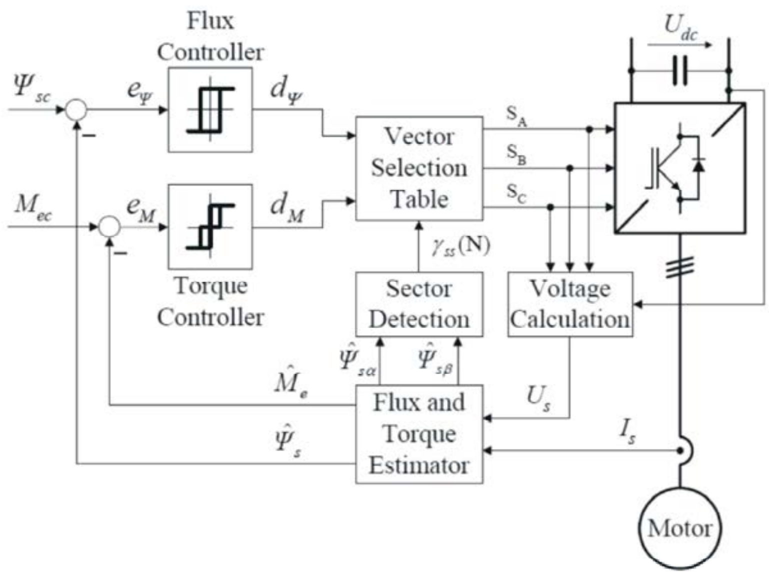

Fig. 7: Block scheme of the direct torque control method

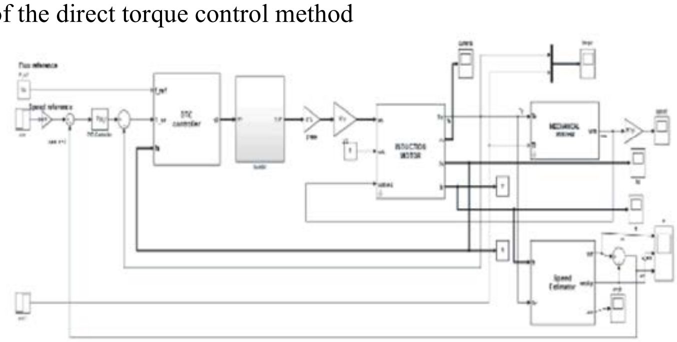

Fig. 8: Direct Torque Control of an Induction Motor Drive

The torque waveform of basic DTC scheme contains large amount of high frequency ripples and it is also reflected in the current waveform. It is clear from the simulation results of DTC-SVM scheme, the torque and current ripples have been reduced. While simulating the basic DTC induction motor drive, the ripple content obtained was about 50% and by the proposed SVM-DTC scheme, the ripple content have been successfully reduced to about 11%.

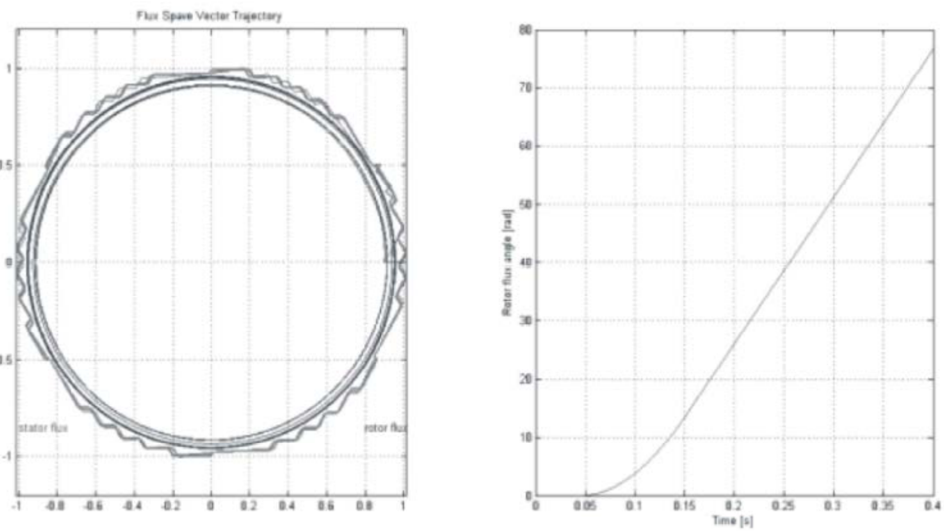

Fig. 9: DTC Flux rotor

Fig. 9 Shown simulation results of DTC-SVM scheme based on flux rotor.

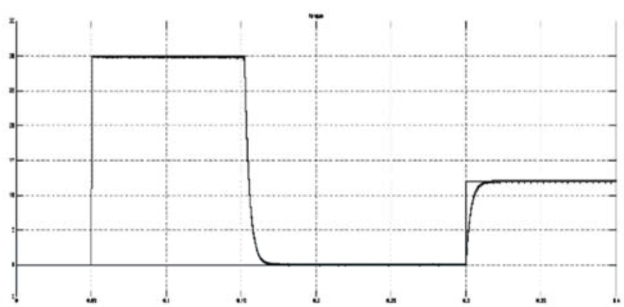

Fig. 10: DTC Torque

Fig. 10 shown simulation results of DTC-SVM scheme based on torque.

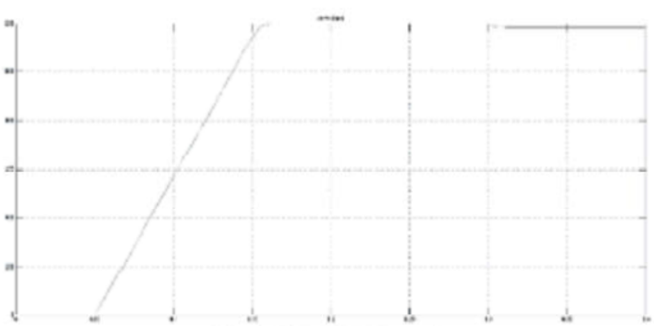

Fig. 11: DTC Speed

Fig. 11 shown simulation results of DTC- SVM scheme based on speed.

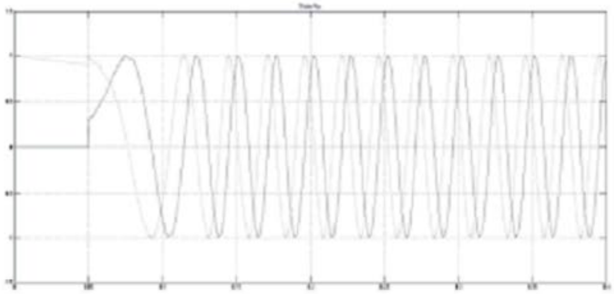

Fig. 12: DTC Stator Flux

Fig. 12 shown simulation results of DTC- SVM scheme based on stator flux.

Fig. 13: DTC Rotor Flux

Fig. 13 shown simulation results of DTC- SVM scheme based on rotor flux.

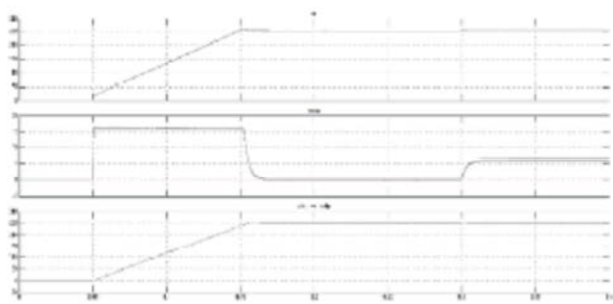

Fig. 14: DTC Windings

Fig. 14 shown simulation results of DTC- SVM scheme based on windings.

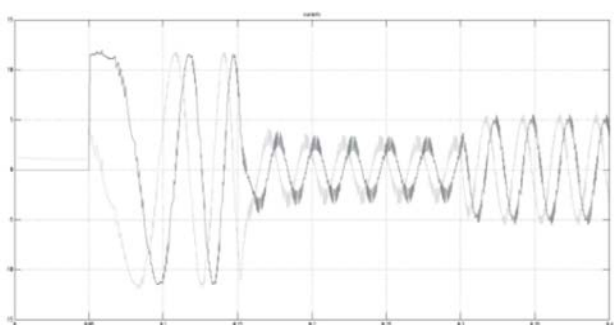

Fig. 15: DTC Current

Fig. 15 shown simulation results of DTC- SVM scheme based on current.

CONCLUSION

This proposed method describes the performance of Direct Torque Control (DTC) based on space vector modulation, improvement model reference system, real time estimation of stator resistance and stator flux estimation. In this system, voltage feeding SVM is more stability because it relies on output voltages from two PI controllers. Depending on the position of the stator flux, it is possible to switch on the suitable voltage vectors to control both flux and torque. The proposed method of DTC-SCM show good performance of torque and flux without ripple as compared with other methods.

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