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Review of Improved Direct Torque Control Methodologies for Induction Motor Drives

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***Abstract*— Decoupled control of induction motor drives is possible using Direct Torque Control (DTC) method which is very simple control strategy compared to field oriented control. In this method direct torque control is achieved by selecting suitable inverter switching voltage vector from a lookup table. But drawback of this method is that it produces toque ripples. Also the switching frequency of inverter switches is not constant. Many methods have been proposed to address these issues of DTC. This paper reviews various methodologies which are suggested to improve performance of basic DTC induction motor drive.**

***Keywords*— DTC, DTCSVM, Induction motor drives, SVPWM**

I. INTRODUCTION

Induction motors(IM) are workhorse of the industry. Over seventy percentage of motors used in industry are three phase induction motors. They are so popular because of simple construction, robustness and maintenance free operation. However, applications where motive power is required at variable speed, DC motors were the only alternative before a decade or two.They were preferred because of ease of control. The reason for non selection of induction motor for variable frequency operation was its complex control structure. Development in filed of processors have made it possible to implement advanced control strategies for IM drives. Vector control method is one of such strategies which controls IM similar to separately excited DC motor [1]. Drawbacks of vector control are complex control scheme and sensitivity to parameter variations [2].Attempts were made to find a control scheme which is less complex and gives good dynamic response for induction motor drives.Direct torque control (DTC) is one of such methods which gives performance comparable to vector control with very less complexity [3].

In classical DTC scheme one voltage vector is selected out of six active and two zero voltage vectors generated by VSI. The selection is done in such a way that torque and stator flux remains within limits of two hysteresis bands. Systematic application of this strategy results into decoupled control of IM without complex co-ordinate transformations, current regulators or PWM pulses. However, due to hysteresis band controllers for torque and stator flux, ripples are produced in torque and stator current, also switching frequency is variable.These problems are more serious at low speed with heavy loads [4].

Many methods have been proposed to address these issues of conventional DTC scheme. This paper reviews various methods suggested to improve performance of classical DTC of IM drives. Methods for performance improvement of classical DTC can be classified in four categories as: (1) DTC with modified lookup table methods (2) DTC with constant switching frequency using SVPWM (3) DTC with predictive control (4) DTC with neuro-fuzzy controller [5-7]. This paper is organized in the following sections. Section II-classical DTC, section III-problems with classical DTC, section IV- DTC with modified lookup table, section V- DTC with SVPWM, section-VI-DTC with fuzzy logic and section VII- conclusion.

II. CLASSICAL DTC

The torque developed by induction motor is directly proportional to angle between stator flux vector and rotor flux vector as shown in following equation.

$$T_e = \frac{L_m}{\sigma L_s L_r}\psi_s\psi_r \sin\gamma_{sr} \qquad (1)$$

The rotor flux vector always follows stator flux vector. By advancing the stator flux vector in phase, angle γ_{sr} can be increased and so the torque developed increases. Similarly by reducing angle γ_{sr}, torque can be reduced. In short direct torque control is possible just by changing position of stator flux vector with reference to rotor flux vector. In classical DTC this movement of stator flux is achieved by selection appropriate switching voltage vector of VSI. Appropriate inverter voltage space vector is selected based on stator flux error and torque error such that stator flux and torque remain within a hysteresis band. Fig.1 shows six active and two non zero voltage space vectors which are possible for two level VSI.

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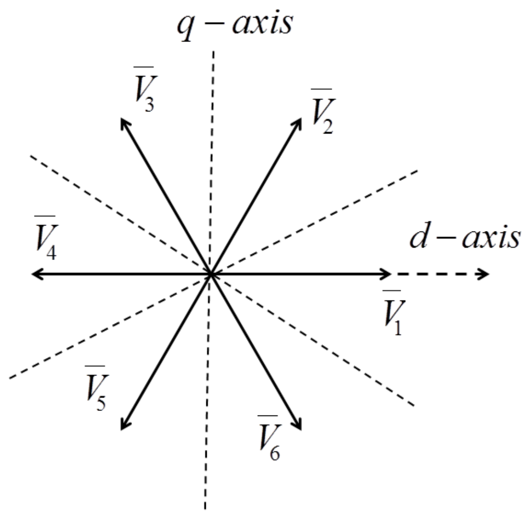

Figure 1Voltage space vectors

Complete block diagram of classical DTC scheme is shown in Fig. 2, where T_e^* and ψ_s^* are reference torque and reference stator flux respectively. Torque error and stator flux errors are processed by three level and two level hysteresis band controllers to generate status signals dT_e and $d\psi_s$ respectively. Based on status of dT_e, $d\psi_s$ and sector θ_i, suitable voltage switching space vector is selected form lookup table to give fast dynamic response and to maintain torque error and stator flux error within hysteresis band. Table-I shows the look-up table used to generate switching voltage vector of VSI.

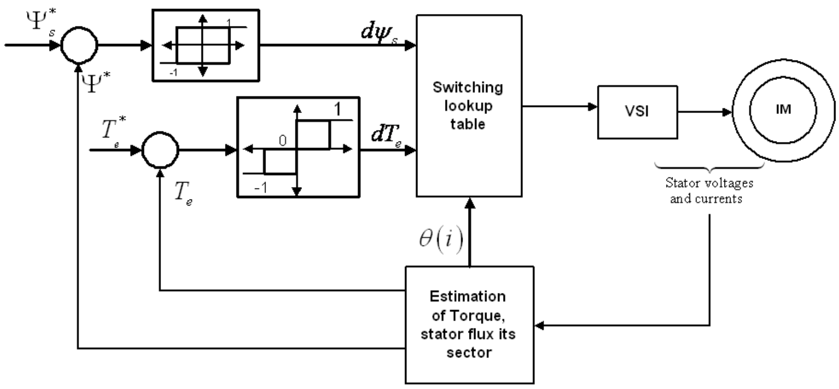

Figure 2 Block diagram of classical DTC scheme

Torque, stator flux magnitude and the sector in which stator flux vector is placed at any instant can be estimated from stator voltages and stator currents. Following equations are used to estimate torque, stator flux and sector information.

$$\psi_{ds} = \int (V_{ds} - R_s i_{ds})dt \qquad (2)$$

$$\psi_{qs} = \int (V_{qs} - R_s i_{qs})dt \qquad (3)$$

$$\psi_{qs} = \sqrt{\psi_{ds}^2 + \psi_{qs}^2} \qquad (4)$$

$$\theta = \tan^{-1}\frac{\psi_{qs}}{\psi_{ds}} \qquad (5)$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \qquad (6)$$

Table 1 Lookup table of DTC scheme

$d\psi_s$	dT_e	$\theta(1)$	$\theta(2)$	$\theta(3)$	$\theta(4)$	$\theta(5)$	$\theta(6)$
1	1	V2	V3	V4	V5	V6	V2
	0	V7	V0	V7	V0	V7	V0
	-1	V6	V1	V2	V3	V4	V5
-1	1	V3	V4	V5	V6	V2	V1
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

Striking advantages of this method is that it achieves decoupled control of torque and flux without complex co-ordinate transformations or PWM signal generation. It only depends on stator resistance hence it is a robust control method. It gives dynamic response quite comparable to vector control but it has some of the drawbacks which are discussed in the following section.

III. PROBLEMS IN CLASSICAL DTC

Torque ripples are produced because of use of hysteresis band controller for torque and flux. It also results into variable switching frequency. Also as discussed in previous section, estimation of stator flux is needed for implementation of classical DTC. Stator flux estimation can be done using voltage model estimation or current model estimation [8]. Current model estimation requires speed sensor and hence generally not used. Voltage model estimation uses pure integration which causes problems at low speeds and caused flux drooping[9].Also at low speed, the stator resistance drop can no longer be ignored, so a boost in stator flux is required. Now when stator flux vector changes the sector, there is no active voltage vector which guarantees the increase in stator flux. As a result there is flux drop at some instances. Thus at low speeds and heavy loads locus of stator flux vector cannot remain circle and becomes more like hexagon, which causes harmonics in stator current. Review of various methods suggested to address these problems is included in the following sections.

IV. IMPROVED DTC WITH MODIFIED LOOKUP TABLE

Modifications in lookup table are mainly aimed at reducing torque ripples. Some of the methodologies are for low speed range also.

A. Reduction of torque ripple by increasing number of switching voltage vectors

This method is also known as discrete space vector modulation(DSVM) [10]. Block diagram of the same is shown in Fig.3.

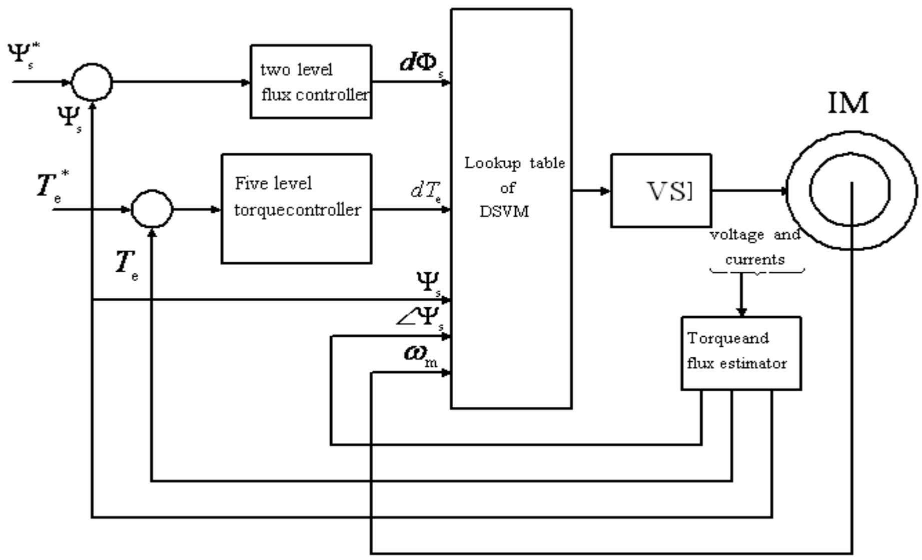

Figure 3 Block diagram of Discrete SVM-DTC

Here conventional three level hysteresis band controller for torque is replaced by five level hysteresis comparator. Suitable switching voltage vector is selected based on status of torque and flux controller, value of stator flux and the information about the sector of stator flux vector. Instead of allowing hysteresis band to change switching voltage vector, a sampling period is used which is divided into n parts. Suitable switching voltage vector is selected for each part. This way number of switching voltage vectors are more compared to basic DTC. More number of switching voltage vectors make it possible to design more accurate switching lookup table. Generally n=3 gives good dynamic performance without much increase in complexity of the look-up table. Fig. 4 shows increased switching voltage vectors after dividing the sampling period in three equal parts in sector-I.

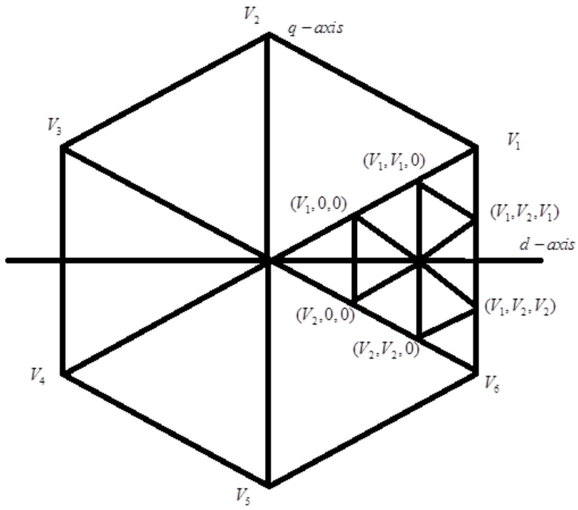

Figure 4 Sectors of DSVM-DTC

Using this technique more appropriate lookup table can be designed for special requirements such as low speed, high speed and starting. Here improved DTC is achieved without going for complex calculations or coordinate transformations. This leads to reduced torque ripples compared to conventions DTC scheme.

B. Modified DTC for low speed range

Reduction in stator flux is caused by stator resistance drop in case of low speeds. This happens because of selection of zero voltage vector for long time. Modified DTC schemes with new lookup table or the one with mixing of dither signals in torque and flux error are suggested to improve operation of induction motor at low speeds and heavy load [11-12].

V. DTC WITH CONSTANT SWITCHING FREQUENCY

One of the main drawbacks of hysteresis band controller in case of basic DTC scheme is that its switching frequency is variable. Because of this problem optimum use of power electronic device used in inverter is not possible. In constant frequency DTC, a voltage pulse width modulator replaces switching lookup table. Closed loop control is achieved by replacing hysteresis band controller with PI, predictive or neuro-fuzzy controller. Reference stator voltage is generated by this controller and it is realized by PWM technique known as space vector PWM or SVPWM [13-15].

A. Space Vector Pulse Width Modulation (SVPWM) Basics

In space vector modulation technique, desired reference voltage is generated by selection of active and zero switching voltage vector to have volt-second balance in sampling period T_s.

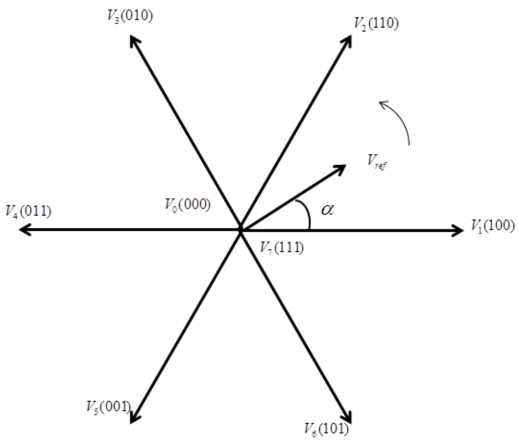

Figure 5 Reference vector generation in SVM-DTC

If reference voltage V_{ref} is to be generated in first sector at an angle α with a-axis as shown in Fig. 5, switching voltage vector V_1 and $V_2$are selected for time T_1 ,T_2 and zero voltage vector for time T_0 in such a way that

$$V_{ref} T_s = V_1 * T_1 + V_2 * T_2 + V_0 * T_0 \qquad (7)$$

To generate sine wave, locus of reference voltage vector should be circle so the switching sequence in sector-I for space vector modulation shall be V0V1V2V7-V7V2V1V0 and so on. Zero vector time T_0 for a sampling period is divided into half and alternatively zero switching vectors V0 and V7 are selected for T_0 in such a way that minimum switching is needed. This well developed space vector modulation scheme can be used to replace lookup table. Torque error and stator flux errors along with stator flux vector angle information can be used to generate desired reference voltage vector using a PI or predictive or fuzzy controller. Closed loop control methods using SVM for DTC are discussed in next sections.

B. DTCSVM with closed loop Flux Control

In this method reference value of stator flux referred to rotor reference frame is calculated from command value of rotor flux ψ_r^* and torque T_e^* .This reference value of stator flux is transformed to stationary reference frame and compared to estimated value of stator flux.
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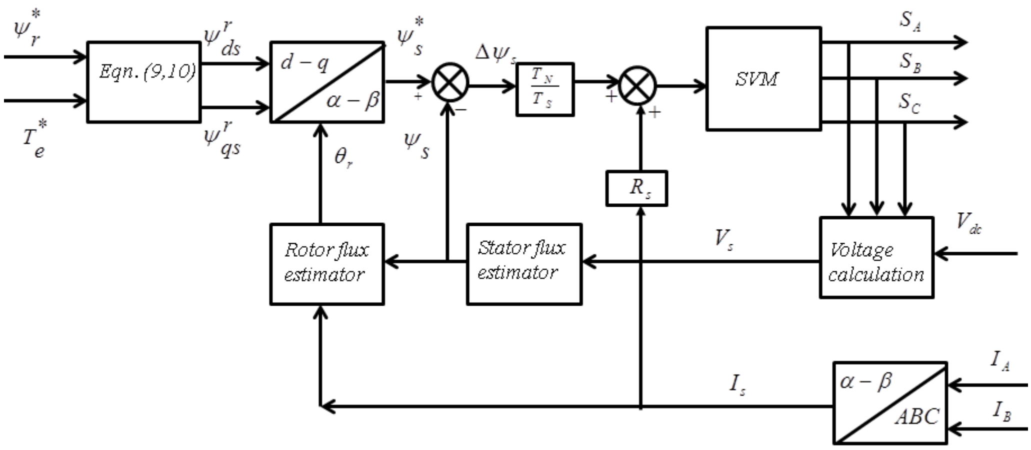

Figure 6 Block diagram of SVMDTC with flux control

Reference voltage vector is generated based on error between reference stator flux, estimated stator flux and stator resistance drop. Now space vector modulation technique is used to generate voltage equal to reference voltage vector. This way it gives closed loop control based on flux and space vector modulation. Here estimation of stator flux and rotor flux both is to be carried out so knowledge of all the motor parameters is needed. Hence it becomes sensitive to parameter variation.

C. DTCSVM with closed loop Torque Control

An alternative approach to DTCSVM is with closed loop torque control as shown in Fig.(4).In this method reference torque is compared with estimated torque to generate $\Delta\gamma_{sr}$ in rotor reference frame. From stator flux value in rotor reference frame and $\Delta\gamma_{sr}$, value of command value of stator flux is generated in stationary reference frame. Reference voltage vector for SVM is generated by comparing command value and actual value of stator flux.

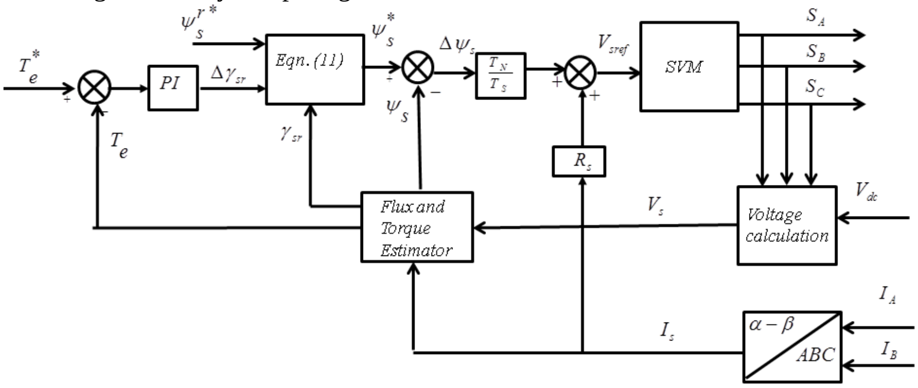

Figure 7 SVMDTC with torque control

This method gives better torque response in dynamic as well as steady state.

D. Predictive SVMDTC scheme

In predictive scheme, torque error and stator flux error are predicted from approximate machine equations [16].Based on these predicted error, suitable reference voltage space vector is selected in such a fashion that error is minimum for that sampling period. For generation of reference voltage space vector from predicted torque and stator flux errors, a quadratic criterion is used. This way selected switching space vector is valid for the whole sampling period and unnecessary switching is avoided. In conventional DTC scheme, the space vector selected may be appropriate at the sampling instant but may not be appropriate for the whole sampling period. Thus by avoiding unnecessary switching, torque ripple can be reduced.

E. Neuro-Fuzzy SVMDTC scheme

Another method to generate reference voltage vector for SVMDTC is using artificial intelligence based controllers [17]. In last decade, application s of AI based controllers are successfully done for control of drives and power electronics. Neuro-Fuzzy (NF) controller is one such AI based controller which combines advantages of both artificial neural networks and fuzzy logic.

In NF-DTCSVM, error signals dT_e and $d\Psi_s$ are fed to NF controller along with stator flux position information. Reference stator voltage vector in polar co-ordinate is decided by NF controller which is used by SVM block.

VI. FUZZY LOGIC DTC

It is quite obvious that in case of classical DTC, none of the inverter state is able to generate voltage space vector which is perfectly suitable to make torque error and stator flux error zero. The reason of ripples in torque or stator flux is that these errors are not quantified as small medium, large, very large and so on. This type of quantification is not possible with hysteresis band controller, but very easily possible for fuzzy logic based systems. In fuzzy logic DTC, torque error, stator flux error and stator flux angle information are converted into fuzzy variables and then fed to fuzzy controller[18]. Switching voltage space vector is decided by fuzzy logic controller based on these fuzzy variables. Selected active voltage vector is applied for the time just enough to achieve torque and flux as per reference value. For rest of the time of sampling period, zero voltage vector is applied.

VII. CONCLUSION

Classical DTC method is having many advantages like inherent speed sensor less control, dependence on stator resistance only, no need for current controllers and simplicity with high performance. The problems associated with classical DTC are torque ripples, variable switching frequency and inferior performance at low speed operation with heavy load. Some of the method reported to improve performance of classical DTC are reviewed in this paper. Modified lookup table methods are suitable for a particular case to reduce torque ripple but they do not guarantee constant switching frequency. Discrete SVMDTC method is simple and effective but it does not give satisfactory

Performance for whole speed range from low to above base speed which is the case with application like automobile or traction drives. SVMDTC methods are so far the best method which gives reduced torque ripples, constant switching frequency but it involves complex computations which make this strategy highly dependent on motor parameters. Hence using this method defeats vary purpose of selecting DTC over vector control for induction motor drives. Other methods like DTC with predictive controller , neural network or fuzzy logic also results in improved performance compared to classical DTC but no single method is suitable for wide range speed control. Also they are far more complex compared to classical DTC. There is wide scope for a control strategy based on DTC which can give improved performance for wide range of speed.

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