

# A Comparative Analysis of Field Oriented Control and Direct Torque Control of Induction Motor Drive

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**Abstract**— Electric Motor Drive System is employed in the various industrial applications such as pumping, air blowing, cooling and compression refrigeration. The motor drive speed control can be achieved by variety of techniques, but an emerging one is Variable Frequency Drive System (VFDS). The motor driven equipment on a typical industrial site accounts for approximately two thirds of the electricity consumption. Now-a-days induction motor is the main work-horse of the industries. So controlling of performance of induction motor is most precisely required in many high performance applications. Scalar control method gives good steady state response but poor dynamic response. While vector control method gives good steady state as well as dynamic response. But it is complicated in structure so to overcome this difficulty, direct torque control introduced. This paper discusses the comparative analysis of Field Oriented Control (FOC) and Direct Torque Control (DTC) methods of Polyphase Induction Motor (PIM) according to their working principle, structure complexity, performance, merits and demerits.

**Keywords**- *Electric Motor Drive Control, Vector Control, Induction Motor, Direct Torque Control (DTC), Field Oriented Control (FOC), Decoupling, Separately Excited DC Motor.*

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## I. INTRODUCTION

An Electrical Motor Drive is defined as a form of machine equipment consist of Electric Motor together with its electronic control equipment & energy transmitting links design to convert electrical energy into mechanical energy and provide electronics control of this process[1].

In 1891 at the Frankfurt exhibition, Nikola Tesla first presented a Polyphase Induction Motor (PIM). Since then great improvements have been made in the design and performance of the induction motors and numerous types of polyphase and single-phase induction motors have been developed. Due to its simple, rugged and inexpensive construction and excellent operating characteristics induction motor has become very popular in industrial applications. As a rough estimate nearly 90 % of the world's AC motors are PIM. AC induction motor is the most common motor used in industries and mains powered home appliances. It is biggest industrial load, so widely used. Engineers have to know its performance, have to control as per load requirement & protecting induction motor also [3].

In the initial years D.C. motors were widely used in applications where high performance in variable speed was required. Separately excited D.C. motors [2] were extremely used in areas where fast torque was a must. It was considered as a main work horse in the industry. The faster dynamic response of DC motor lies into its being a doubly fed motor and inherent De-Coupling facility of independent control of torque and flux in the motor. DC motor had its disadvantage like maintenance, sparking, difficulty in commutation at high current and voltage so it is limited to low power and low speeds.

After the invention of the PIM above mention difficulties was overcome. But it did not have de-coupling facility between torque and flux for controlling. So their dynamic performance was poor. After the invention of static DC controller, DC machines were again widely used for torque and speed control. Then after invention of Power Semiconductor Devices (PSD)[9] and scalar control method like Variable Frequency Drive (VFD) or slip frequency control, induction motors were widely used again but they didn't have de-coupling facility of torque and flux. So for the de-coupling of torque and flux, vector control introduced for better performance of induction motor application.

Slip frequency control method is well known method for better dynamic performance. This method was widely used in all high performance induction machine drives until Field Oriented Control (FOC) became the industry's standard for AC drives with dynamics close to that of DC motor drives [4].

Direct Torque Control (DTC) has emerged over the last decade to become one possible alternative to the well-known Vector Control of PIM. Its main characteristic is the good performance, obtaining results as good as the classical vector control but with several advantages based on its simpler structure and control diagram. Which has simpler construction and working principle and cheaper than FOC [5]. This paper discusses the comparative study between FOC and DTC method of control of induction motor.

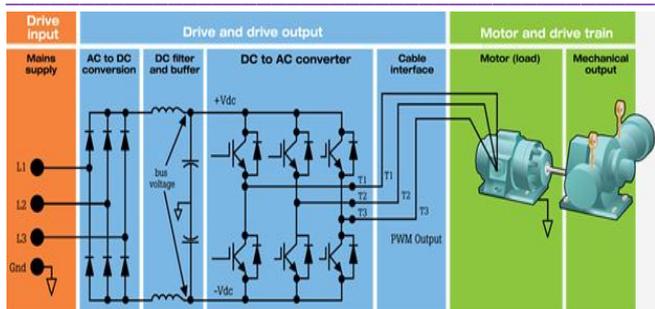


Fig.1 Block Diagram of Electric Motor Drive System

## II. STUDY OF FIELD ORIENTED CONTROL (FOC)

Before introduction of Vector Control of PIM the methods enjoyed wide acceptability in controlling the speed of the cage induction motor drive are termed as Scalar Control, V/f control, Voltage Control, Frequency Control, Power Recovery Control etc. all these control methods with cage motor exhibits inferior dynamics performance as compared to separately excited DC motor. So the modern research is carried on introducing and improving Vector control which involves both magnetic and phase alignment of quantities [4] [5].

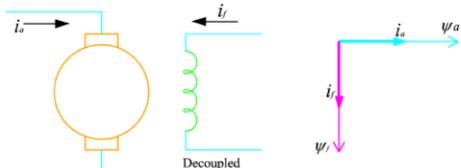


Fig. 2 Equivalent Circuit of DC Machine.

Vector Control (VC) mode of operation is defined as a control technique in which two equivalent control signals are produced to control torque and flux in decoupled manner. When PIM is operated in VC mode, its response improves considerably and it acts as a better substitute for the separately excited DC motor.

The field and the armature currents respectively can control the flux and torque, independently in the case of DC motors. It is because of this inherent decoupling between the field flux and the armature current, one is able to achieve very good torque dynamics from DC machines. Therefore, achieving good torque dynamics in AC machines is not easy. However, now-a-days, field oriented control or vector control techniques have been employed, which results in good torque dynamics of induction motors.

Inverter fed induction motors are increasingly being used for general purpose applications. Varying input voltage (V) to the motor frequency (f) in open loop operation is one of the most popular methods of speed control. This is called scalar control method. In this method, V/f is held constant. As the frequency nearly approaches zero, the magnitude of the stator voltage also tends to zero and the stator resistance absorbs this low voltage. Therefore, at low speeds an auxiliary voltage must be injected for compensating stator resistance drop so that the rated air-gap flux and hence the full load torque is available up to zero speed. Hence, in constant v/f control scheme, the air gap flux may drift as a result, torque sensitivity with slip frequency or stator current will vary. Hence, a speed control scheme with independent control of torque and flux loop is desirable.

In 1971, Blaschke proposed a scheme, which aims at the control of induction motor like a separately excited dc motor, called "Field Oriented Control or Vector Control". In an AC machine, both the phase angle and the modulus of the current must be controlled, or

in other words, the current vector must be controlled. This is the reason for the terminology 'Vector Control'. In this scheme, the induction motor is analyzed from a synchronously rotating reference frame where all the fundamental ac variables appear to be dc equals. The torque and flux components are identified and controlled independently to achieve good dynamic response. Vector control implies that an ac motor is forced to behave dynamically as a DC motor by the use of feedback control.

FOC or VC of PIM achieves decoupled torque and flux dynamics leading to independent control of the torque and flux as for a separately excited DC motor. This is achieved by orthogonal projection of the stator current into a torque-producing component and flux-producing component. This technique is performed by two basic methods. Direct and indirect vector control. FOC can be implemented as indirect (feed-forward) or direct (feedback) depending on the method used for rotor flux identification. The direct FOC determines the orientation of the air-gap flux by use of a hall-effect sensor, search coil or other measurement techniques. However, using sensors is expensive because special modifications of the motor are required for placing the flux sensors. Furthermore, it is not possible to directly sense the rotor flux. Calculating the rotor flux from a directly sensed signal may result in inaccuracies at low speed due to the dominance of stator resistance voltage drop in the stator voltage equation and inaccuracies due to variations on flux level and temperature. In case of induction machines, the indirect method is based on reconstruction (estimation) approaches employing terminal quantities such as voltage and currents in a motor model to calculate the flux position. Indirect FOC does not have inherent low-speed problems and is therefore preferred in most applications. There are three possible implementation based on the stator, rotor, or air gap flux orientation. The rotor flux indirect vector control technique is the most widely used due to its simplicity.

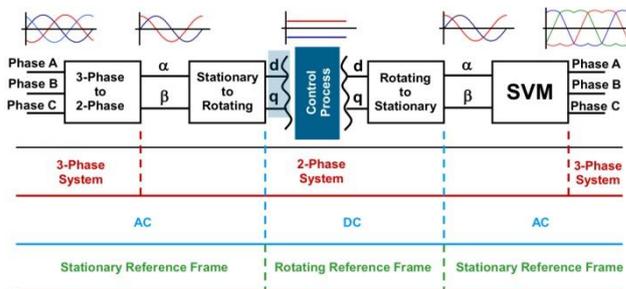


Fig. 3 Concept of Space Vector Modulation

FOC methods are attractive but suffer from one major disadvantage. They are sensitive to parameter variations such as rotor time constant and incorrect flux measurement or estimation at low speeds. Consequently, performance deteriorates and a conventional controller such as a PI is unable to maintain satisfactory performance under these conditions [2] [5].

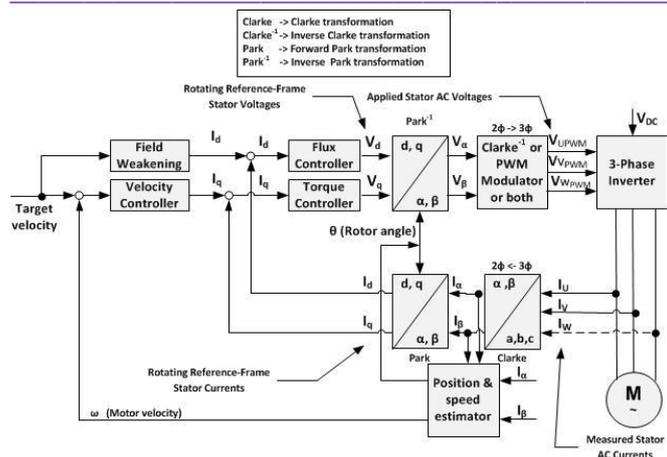


Fig. 4 Field Oriented Control of Induction Motor

The Field Orientated Control is based on three major points: the machine current and voltage space vectors, the transformation of a three phase speed and time dependent system into a two co-ordinate time invariant systems and effective Pulse Width Modulation pattern generation [6].

### III. MODELLING OF FIELD ORIENTATION CONTROL

As shown in Fig. 2 construction of DC machine is such that field flux  $\Psi_f$  produced by the field current  $I_f$  is perpendicular to the armature flux  $\Psi_a$  produced by the armature current  $I_a$ . These are decoupled in nature. This means that torque is individually controlled by the current  $I_a$ , without affecting the  $\Psi_f$  and we get fast transient response and high torque/ampere ratio with rated  $\Psi_f$ .

As shown in Fig. 3, DC machine-like can also be extended to an induction motor if the machine control is considered in a synchronously rotating reference frame (d-q) where the sinusoidal variables appear as DC quantities in steady state.

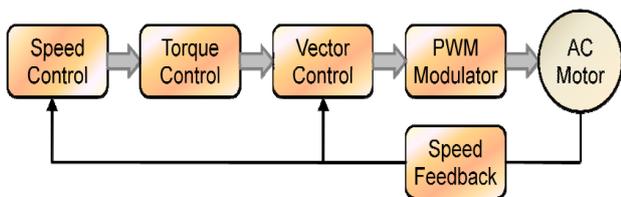


Fig. 5 Block diagram of Field Orientated Control of AC Drive.

There are three ways of vector control based on the reference frame in which the stator currents are transformed. They are:

- (1) Stator flux oriented control
- (2) Magnetizing flux oriented control
- (3) Rotor flux oriented control

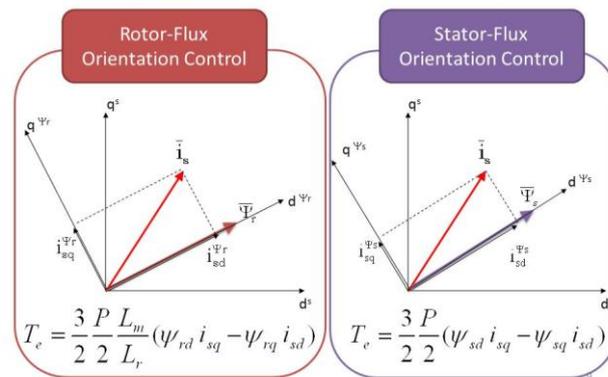


Fig. 6 Vector diagram for Flux oriented control method

#### (1) Stator Flux Oriented Control

In stator flux oriented control, the stator quantities are transformed into a reference frame which rotates at the speed of stator flux linkage vector. The rotor current is replaced by:

$$i_{ms} = (1 + \sigma)i_s + i_r e^{-j\theta r} \quad (1)$$

By this substitution there exists an inherent coupling between flux and torque producing components. Hence, separate decoupling circuits are needed. This delays the control action. The decoupling circuit for voltage controlled voltage source inverter (VSI) is simpler and can be easily implemented. Since current control is preferable for high performance drives this is not an obvious choice.

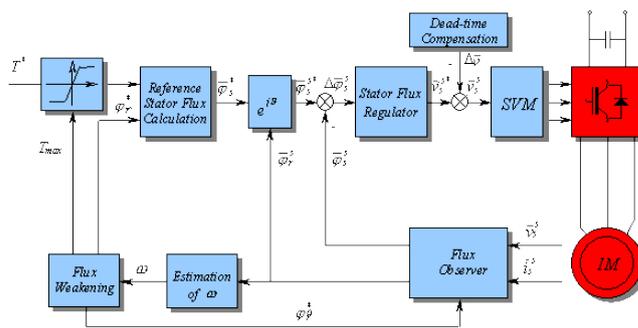


Fig. 7 Block diagram of Stator Flux Oriented Control method

#### (2) Magnetizing Flux Oriented Control

In magnetizing flux oriented control, the stator quantities are transformed into a reference frame which rotates at the speed of magnetizing flux linkage vector.

The rotor current is replaced by:

$$i_m = i_s + i_r e^{j\theta r} \quad (2)$$

By this substitution, there also exists coupling between flux and torque producing components. The decoupling circuit required for independent control of flux and torque is very complex. Hence, this method is rarely used.

#### (3) Rotor Flux Oriented Control

In Rotor Flux Oriented (RFO) control [7], the motor quantities are transformed into a reference frame which rotates at the speed of rotor flux linkage. The rotor current vector is replaced by  $i_{mr}$ , which is expressed as:

$$i_{mr} = i_s + (1 + \sigma_r)i_r e^{-j\theta r} \quad (3)$$

Where,

$i_{mr}$  = rotor magnetizing current in stationary frame.

$\sigma_r$  = the rotor leakage factor

Using the expression for  $i_r$  in stationary reference frame is given by:

$$i_r e^{-j\theta_r} = (i_{mr} - i_s) / (1 + \sigma_r) \quad (4)$$

The expression for torque becomes:

$$T_e = \frac{Lm^2 \rho i_{mr} i_s \sin\delta}{2Lr} \quad (5)$$

Where,

$\delta$  = angle between field frame and rotor frame

The current vectors  $i_s$  and  $i_{mr}$  are transformed into a reference frame which rotates at the speed of rotor flux linkage vector. In rotor flux oriented reference frame, the  $i_{mr}$  has only d – axis component, which is equal to  $i_{mr}$  (represents the magnitude of  $i_{mr}$ ). The expression for  $i_s$  in rotor field oriented reference frame is given by:

$$i_s e^{-j\rho_r} = i_{sx} + i_{sy} \quad (6)$$

Where,

$\rho_r$  = angle between the rotor field reference frame and stationary reference frame.

$i_{sx}$  = d – axis component of stator current in rotor field reference frame.

$i_{sy}$  = q – axis component of stator current in rotor field reference frame. Now the torque equation becomes:

$$T_e = \frac{Lm^2 \rho i_{mr} i_{sy}}{2Lr} \quad (7)$$

This equation is similar to that of DC motor's torque equation where  $i_{mr}$  is similar to field current and  $i_{sy}$  similar to armature current of DC motor.

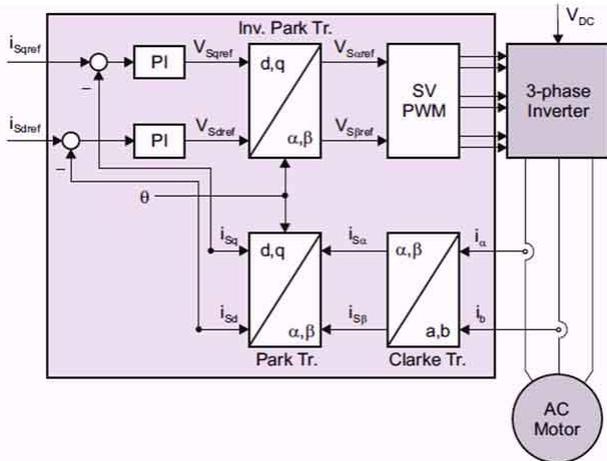


Fig. 8 Block diagram of Rotor Flux Oriented Control method

The goal of FOC is to maintain the amplitude of the rotor flux linkage at a fixed value, except for field-weakening operation or flux optimization, and only modify a torque-producing current component in order to control the torque of the ac machine. This control strategy is based on projections. Electromagnetic torque is produced by the interaction of stator flux linkages and stator currents (or rotor flux and rotor current), and can be expressed as a complex product of the flux and current space Phasor.

There are two types of FOC: (1) Direct & (2) Indirect

**(1) Direct FOC**

In direct field-oriented control the rotor flux position is obtained by measuring the air gap flux using sensors or estimated using terminal voltages and currents, which is also known as sensor less

direct field oriented control. Knowing the flux position the required phase currents that give the desired flux and torque value can be calculated and forced into the motor stator [5].

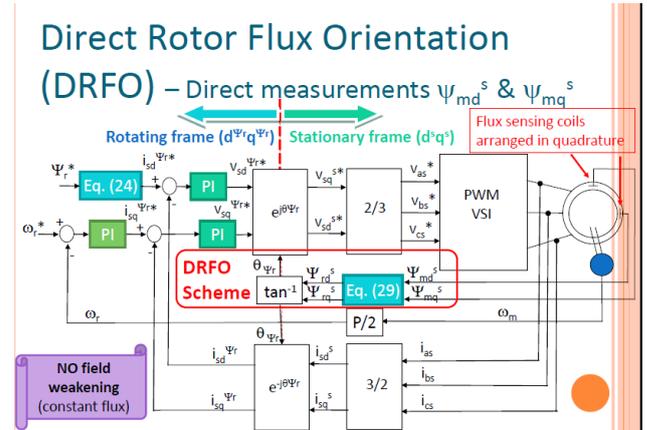


Fig. 9 Block diagram of Direct Rotor Flux Oriented Control method

In indirect field-oriented control the 90-degree orientation between the rotor flux and the q-axis component of the stator current is maintained by satisfying the unique slip relationship associated with the d-q currents components in a field-orientation controlled motor. In this method, a feedback of the rotor position is required. Similar to the rotor flux position in direct field-oriented control case the rotor position can be directly obtained from an incremental encoder or estimated using the terminal voltages and currents information which is known as sensor less indirect field-oriented control [5],[8],[9],[10],[11],[12].

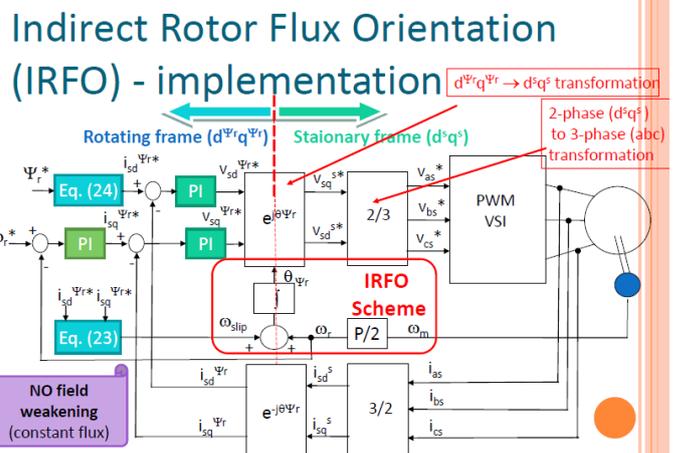


Fig. 10 Block diagram of Indirect Rotor Flux Oriented Control method

**IV. DIRECT TORQUE CONTROL**

Direct torque control was developed by Takahashi [13] and Depenbrock [14] as an alternative to field-oriented control [15], [16]. DTC is a control philosophy exploiting the torque and flux producing capabilities of ac machines when fed by a simple voltage source inverter that does not require current regulation loops, still attaining similar performance to that obtained from a vector control drive.

In a direct torque controlled (DTC) induction motor drive supplied by a voltage source inverter, it is possible to control directly the stator flux linkage  $\lambda_s$  (or the rotor flux  $\lambda_r$  or the magnetizing flux  $\lambda_m$ ) and the electromagnetic torque by the selection of an optimum inverter voltage vector.

The selection of the voltage vector of the voltage source inverter is made to restrict the flux and torque error within their respective flux and torque hysteresis bands and to obtain the fastest torque response and highest efficiency at every instant. DTC enables both quick torque response in the transient operation and reduction of the harmonic losses and acoustic noise.

With DTC there is no modulator and no requirement for a tachometer or position encoder to feed back the speed or position of the motor shaft.

In DC drive armature current and magnetizing current are control variables whereas in DTC, motor torque and motor magnetizing flux are control variable.

Both drives use actual motor parameters to control torque and speed which shows better dynamic performance. In DTC, no tachometer or encoder is needed to feedback a speed or position signal [5].

DTC is the first technology to control the “real” motor control variables of torque and flux.

It beneficial because torque and flux are motor parameters that are being directly controlled, there is no need for a modulator, as used in PWM drives, to control the frequency and voltage. DTC also provides precise torque control without the need for a feedback device.

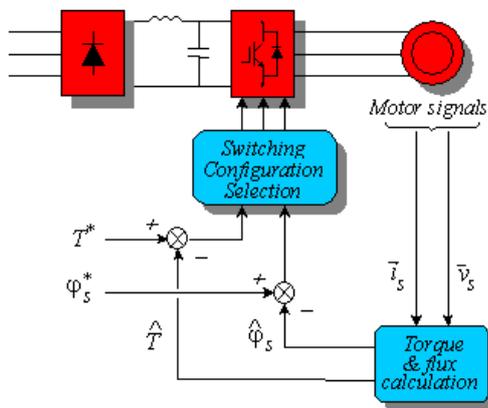


Fig. 11. Block diagram of DTC

In principle, the DTC method selects one of the inverter’s six voltage vectors and two zero vectors in order to keep the stator flux and torque within a hysteresis band around the demand flux and torque magnitudes. The torque produced by the induction motor can be expressed as:

$$T = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r L_s} |\psi_s| |\psi_r| \sin \rho \quad (8)$$

This shows the torque produced is dependent on the stator flux magnitude, rotor flux magnitude, and the phase angle between the stator and rotor flux vectors. The induction motor stator equation can be approximated as

$$\vec{V} = \frac{d\vec{\Psi}}{dt} \quad (9)$$

Over a short time period if the stator resistance is ignored. This indicates that the change in the stator flux vector is determined by the applied voltage vector.

If a voltage vector changes then the stator flux and phase angle between the stator flux and rotor flux vectors changes, then the torque produced will change. Since a two-level inverter is only capable of producing six non-zero voltage vectors and two zero vectors, it is possible to create a table that determines the voltage vector to apply based on the position of the stator flux and the required changes in stator flux magnitude and torque. This is called the optimal vector selection table.

The estimated stator flux magnitude and torque output is compared to the demand values. A voltage vector is then selected that will drive the torque and flux towards the demanded values [21].

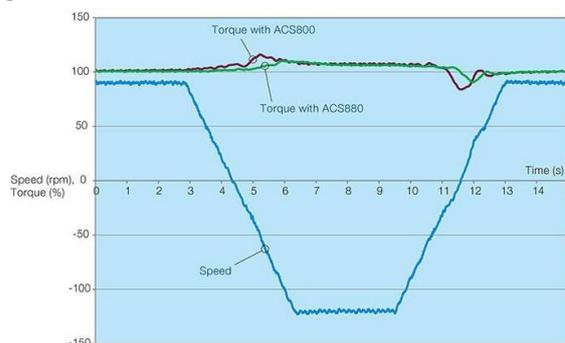


Fig. 12 Speed Torque Characteristics for FOC and DTC

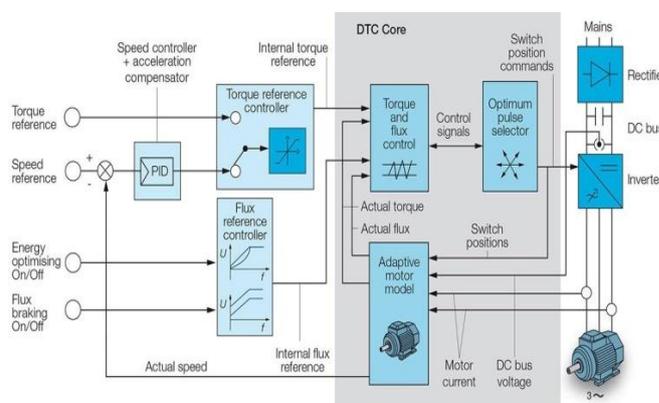


Fig. 13 DTC Controller

## V. COMPARATIVE STUDY OF FOC AND DTC

R. H. Park [17] introduced rotating reference frames in 1929, then after many years FOC was developed which results in decoupling of torque and field excitation which is similar in performance with DC separately excited motor control. Hannakam [18] developed a dynamic model of induction machine with analog computer in 1959. Then the concept of Indirect FOC (IFOC) presented by Hasse in 1968 [19]. In 1971, Direct FOC (DFOC) was developed within Siemens by Blaschke [20].

Both authors proposed an orientation aligned with the rotor flux vector. In 1980s, Depenbrock presented the Direct Self Control (DSC) [14] and Takahashi and Noguchi the Direct Torque Control (DTC) [13].

Unlike FOC which includes pulse width-modulated current control loops, DSC and DTC are hysteresis controls working directly with stator flux and torque without having the need for an

inner current control loop [2], [18]. Each drive ran a 15 kW, four-pole induction motor at its rated torque reference and with the load machine controlled to make slow speed reversals near zero speed.

Field-oriented control in induction motor is sensitive to deviation in estimated motor parameters values used in the control algorithm from their actual values. In addition, the parameters values may need to be updated while the motor is running, if there are large changes in the operating temperature and flux magnitude because resistances values depend on the temperature and inductances values changes due to flux saturation. The desired field orientation torque characteristic cannot be achieved unless the controller provides real time tuning for the parameters values. Direct field orientation requires values of the rotor leakage inductance and the ratio of the rotor inductance to the mutual inductance while the first parameter has a constant value independent of temperature and flux the second parameter is moderately affected by the saturation of the main flux path in the motor. In addition, there is the need for the special flux sensors, which need frequent maintenance and impose limitation in the motor mounting. If the sensorless form of direct field orientation is implemented, the values of the stator resistance and inductance are needed beside the above parameters. The value of the stator resistance is sensitive to temperature changes. If sensors are used to measure the flux, the parameters values mismatch will affect the steady state torque values but not the dynamics response, if flux is estimated the dynamic response will deteriorate. Indirect field orientation is more sensitive to parameters values inaccuracy than direct field orientation. The value of the rotor time constant is used in the slip frequency calculation this parameter is sensitive to temperature and flux level. The need of special position incremental encoder is another disadvantage of the method [26].

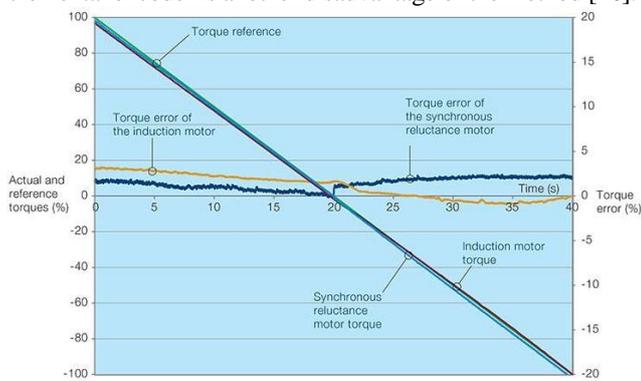


Fig. 14 Torque Reference and Torque error Speed Torque Characteristics for FOC and DTC

It is drive's sensor less torque control accuracy was compared using a four-pole induction motor and a synchronous reluctance motor of 15 kW size (at 50% of rated speed). DTC held torque error to only a small percent of rated torque for both motor types.

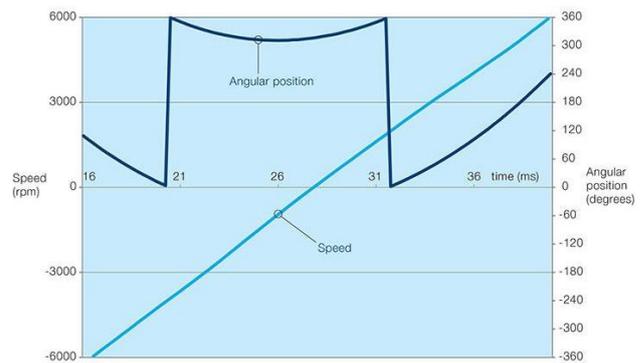


Fig. 15 Relation between Speed and Angular Position of the Induction Motor Drive with FOC and DTC.

Speed and angular position of a 1.5 Nm, 6,000 rpm PM synchronous motor were measured during speed reversal between  $\pm 6,000$  rpm in less than 25 milliseconds (ms). This is very close to the motor's mechanical time constant of 24 ms and a theoretical limit.

Beside the above limitations, field-oriented control is complex and need fast speed micro-controllers. These limitations make an alternative method known, as direct torque control an attractive method because it has a simple algorithm that does not include phase transformation, does not need special position or flux sensors, PI regulators, current regulators and PWM signals generators (no timers) [24],[26].

Direct Torque Control (DTC) is an optimized simple induction motor drive control principle where inverter switching directly controls the motor flux and torque. It can be implemented without the use of speed and flux sensors, reducing the cost and eliminating the need for regular maintenance. It does not require any coordinate transformation, which would increase the computational burden. Another advantage of DTC over field-oriented control is that it depends only on the value of the stator resistance, so it is less sensitive to parameter value variations. The measured input values to the DTC control are the motor currents and voltages. The voltages can be defined from the DC-bus voltage and the inverter switch positions without the use of sensors. The voltage and current signals are inputs to the flux and torque estimator, which produces the values of stator flux and torque at a specific switching period. Motor torque and flux hysteresis comparators compare the actual values to the reference values of the torque and the flux. The outputs from these comparators are updated every switching period and they indicate how the torque and flux have to be varied. Depending on the outputs from the comparators, the switching logic directly determines the optimum inverter voltage vector. The simplicity of the DTC method comes with some disadvantages, the main one being the high torque ripple. The main reason for the torque ripple in the conventional DTC is that the selected voltage vector is applied for the complete switching period regardless of the magnitude of the torque error, resulting in a wide torque hysteresis band. A better drive performance can be achieved by varying the duration of applying the selected voltage vector during each switching period according to the magnitude of the torque error and the position of the stator flux, which will result in a small torque hysteresis band and hence less torque ripple [22], [26],[27].

TABLE 1.  
COMPARISON OF FIELD ORIENTATED CONTROL & DIRECT TORQUE CONTROL

PARAMETER	FOC	DTC
Transformation	Present	Void
Dynamics	high	high
Robustness	Robust	Robust
Torque Response	Good	Best & Fast
Speed sensor	Necessary	Less necessary
Parameter sensitivity	Big	Average
Control close	Necessary PWM	Not of PWM
Decoupling	Necessitate orientation	Natural
Regulators	Three stator regulator (Hysteresis)	Torque regulator Flux regulator
Construction	Complex	Simple
Speed Control	Accurate	Good
Cost	Costly	Less Costly
Steady state performance	Best	Good
Dynamic performance	Relatively low	Relatively high
Torque and current ripple	Low	High
Errors due to parameter detuning	High	Low
Switching frequency change with speed	Comparatively less	High

FOC and DTC are different on the operation principle but their objectives are the same. Both control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any extraneous disturbances. Both are practically implemented and widely used in industry. The comparison as per TABLE I is based on various criteria including basic control characteristics, static and dynamic performance, and implementation complexity [23], [24], [25], [27], [28], [29].

## V. CONCLUSIONS

From the comparative study between FOC and DTC in this paper, discussion conclude that DTC is simple principle, construction, control & give dynamic performance nearly same as FOC. But it has higher ripple contents in stator current and electromagnetic torque which creates nonlinearity to supply. Whereas FOC is complex in principle, construction, control & give steady state performance better than DTC but lower dynamic performance than DTC. If controller of DTC properly designed then performance will met that of FOC. By using DSP, FPGA & microcontroller and also using artificial

intelligence techniques this task can be achievable. Also cost wise DTC is cheaper than FOC. So mostly DTC used compared to FOC. But wherever high performance operation precisely required FOC is more preferable than DTC.

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