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State of Art of PMSM Speed Control Using DTC and FOC Techniques

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ABSTRACT*:* Permanent magnet synchronous motors have attracted increasing interest in recent years for industrial drive application. The availability of low-cost power electronic devices and the improvement ofPM characteristics enable the use of PM motors even in some more demanding applications. The output torque and stator current exhibit a complicated function relation. Magnetic field can be decoupled to get a good control performance. This paper focuses on the study of the two common vector control methods – FOC and DTC on PMSM. The various advantages and characteristics of the two control methods were identified and thus concluded that both the methods can be applied as an optimized method for PMSM control in various applications.

KEYWORDS*:* Permanent Magnet Synchronous Motor (PMSM), Field Oriented Control (FOC), Direct Torque Control (DTC).

I.INTRODUCTION

Since the last three decades AC machine drives are becoming more popular, especially Induction Motor (IM) and Permanent Magnet Synchronous Motor (PMSM), but with some special characteristics, the PMSM drives are ready to meet up sophisticated needs such as fast dynamic response, high power factor, and wide operating speed range. As a result, a gradual gain in the use of PMSM drives will surely be witnessed in the future in low and mid power applications. In a PMSM, the dc field winding of the rotor is replaced by a permanent magnet to produce the air-gap magnetic flux. Having the magnets on the rotor, electrical losses due to field winding of the machine get reduced and the lack of the field losses improves the thermal characteristics of the PM machines and its efficiency. Absence of mechanical components like brushes and slip rings makes the motor lighter, high power to weight ratio for which a higher efficiency and reliability is achieved [1]-[3]. Owing to its remarkable characteristics of strong coupling, nonlinearity and multivariable nature, application of PMSMs are increasingly found in areas such as national defence, agriculture, robotics, aerospace technologyand daily life [4].

Nowadays, the most widely used techniques for controlling PMSMs are Field Oriented Control (FOC) and Direct Torque Control (DTC). FOC is based on vector control, which controls the PMSM's stator currents components in a rotating reference frame. In this technique the machine's stator currents are categorized into flux and torque producing components. The q axis carries the torque component and the d axis carries the flux component, eventually resulting in the torque and flux control [5]. The DTC technique is a kind of high performance variable-frequency adjusting-speed technique in the AC drives and is studied widely after the vector control (VC) technique. DTC for PMSM has the major advantages of simple structure, fast torque response, good robustness etc. [6]. The working principle for the basic DTC is to select a voltage vector based on the error between sensed and estimated values of torque and flux, rotor position estimation. DTC has the capability to work without any external measurement sensor for the rotors mechanical position. To satisfy the correct direction of rotation of a PMSM, the rotor position is required at the motor start up. The advantage of the DTC is to eliminate the dq-axes current controllers, associated transformation networks, and the rotor position sensor. The disadvantages are low speed torque control difficulty, high torque and current ripple value, variable switching frequency, high noise level in low speed range [7]. These control techniques are different in their principle of operation but their objectives aim both to control effectively the motor's torque and flux parameters in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any external disturbances. Both the control strategies have been successfully implemented in industrial products [8].

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II.PERMANENT MAGNET SYNCHRONOUS MOTOR

A. Constructional Features.

The Permanent Magnet Synchronous Motor is an AC synchronous motor whose field excitation is provided by permanent magnets, but has a sinusoidal Back EMF waveform. The key characteristics of PMSM includes that it has no sparks, it is cleaner, faster, less noisy, more efficient and reliable. It is designed for high performance servo applications and when it is coupled with FOC, it produces optimal torque. A PMSM provides rotation at a fixed speed in synchronisation with the frequency of the power source, regardless of the fluctuation of the load or line voltage. The motor runs at a fixed speed synchronous with mains frequency, at any torque up to the motor's operating limit. PMSMs are therefore suitable for high-accuracy, fixed-speed drives.The stator has axial slots inside, in which three phase stator winding is placed. The stator is wound with a three phase winding for a specific number of poles equal to the rotor poles. Most PMSMs utilize permanent magnets which are mounted on the surface of the rotor. This makes the motor appear magnetically "round", and the motor torque is the result of the reactive force between the magnets on the rotor and the electromagnets of the stator. This results in the optimum torque angle being 90 degrees, which is obtained by regulating the d-axis current to zero in a typical FOC application. However, some PMSMs have magnets that are buried inside of the rotor structure. These motors are called Interior Permanent Magnet, or IPM motors. As a result, the radial flux is more concentrated at certain spatial angles than it is at others. This gives rise to an additional torque component called reluctance torque, which is caused by the change of motor inductance along the concentrated and non-concentrated flux paths. This causes the optimum FOC torque angle to be greater than 90 degrees, which requires regulating the d-axis current to be a fixed negative ratio of the q-axis current. This negative d-axis current also results in field weakening, which reduces the flux density along the d-axis, which in turn partially lowers the core losses.

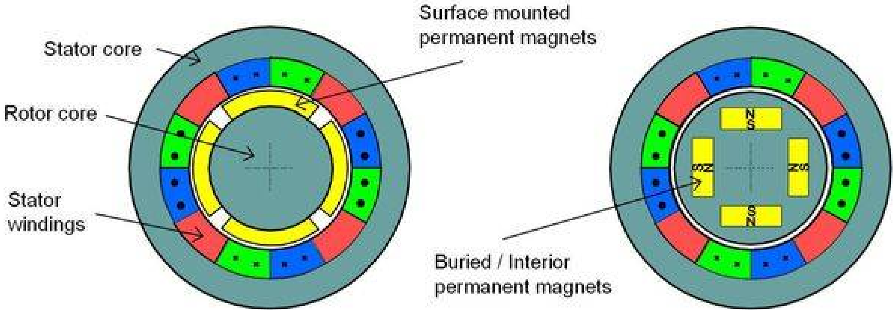

Fig. 1 Structure of Surface mounted PMSM and Interior PMSM

B. Model of PMSM.

The model of PMSM without having damper winding has been developed on rotor reference frame using the following assumptions (i) the induced EMF is sinusoidal, (ii) eddy currents and hysteresis losses are negligible, (iii) there are no field current dynamics, (iv) the stator windings are balanced with sinusoidally distributed magneto-motive force (mmf). The voltage equations of the IPMSM dynamics in the synchronous reference frame are obtained as shown in equation (1) and (2).

$$v_d = r_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \tag{1}$$

$$v_q = r_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \varphi_m \tag{2}$$

We understand from the above equations that the coupling terms $-\omega L_q i_q$and$\omega L_d i_d$are originated from the rotating coordinate and they make an interference between d and q dynamics. The rotor flux linkage is equivalently expressed as a product of d axis inductance, L_d and a virtual current, $i_f$as shown in equation (3).

$$\varphi_m = L_d i_f \tag{3}$$

With i_f, a PMSM equivalent circuit is depicted as shown in figure 2.

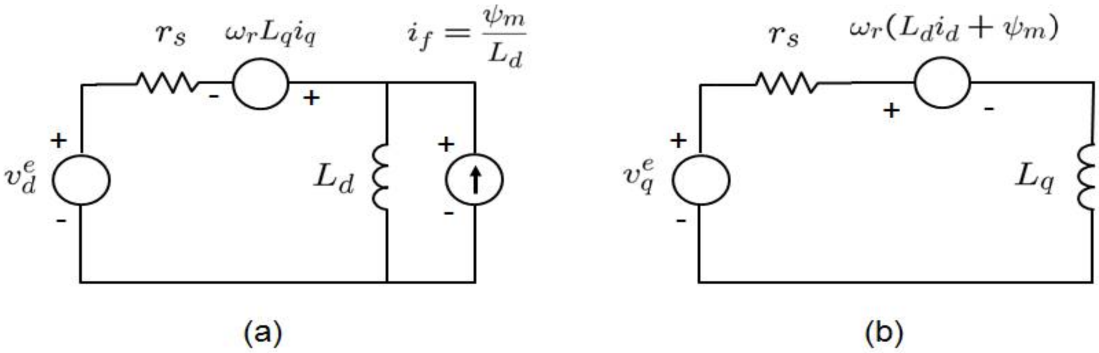

Fig. 2 Equivalent circuit of PMSM: (a) *d* axis and (b) *q* axis

The torque is obtained by the cross product of stator flux linkage and stator current. With the right hand rule, torque is obtained in the axial direction. The torque equation of PMSM in the synchronous reference frame will be as in equation (4).

$$T_e = \frac{3P}{4}\omega_r\left(\varphi_m i_q + \left(L_d - L_q\right)i_d i_q\right) \tag{4}$$

It can be noted that$\varphi_m i_q$is the electromagnetic torque based on Lorentz force, whereas$\left(L_d - L_q\right)i_d i_q$is the reluctance torque caused by the $\left(L_d - L_q\right)$asymmetry.

C. Advantages, Limitations and Applications.

The high efficiency, high steady state torque density and simple controller of the PM motor drives when compared with the induction motor drives, make them a good alternative in certain applications. The torque to inertia ratio of the PMSM is higher because of the absence of the rotor cage, which allows for a faster response for a given electric torque. The induction machine requires a source of magnetizing current for excitation but the PM machines already has the excitation in the form of rotor magnets. The need for magnetizing current and the fact that the IM has a lower efficiency necessitate for a large rectifier and an inverter for the IM than for a PM machine of the same output capacity. The PM machine is smaller in size than an IM motor of same capacity. Thus, it's advantageous to use PM machine, especially where space is a serious matter. The limitation of the PMSM control is that the ripple will be high at low speeds. Also, the power factor of operation cannot be controlled as field winding cannot be controlled which in turn leads to losses and further decreases the efficiency. Another main drawback of the PMSM is the use of position sensor which leads to additional electronics, extra wiring, extra space, frequent maintenance and careful mounting which detracts from the inherent robustness and reliability of the drive [9]. The applications of PMSM are found in the areas of Air conditioner and refrigerator (AC) compressors, Direct-drive washing machines, automotive electrical power steering, machining tools, traction control and data storage.

III. IMPLEMENTATION

A. Field Oriented Control (FOC)

The fundamental principle of FOC is that High-performance motor control is characterized by smooth rotation over the entire speed range of the motor, full torque control at zero speed, and fast accelerations and decelerations. The basic idea of the FOC algorithm is to decompose the stator current into the magnetic field-generating part and the torque-generating part. Both components can be controlled separately after the decomposition. The structure of the motor controller is then as simple as that for separately excited DC motors. The basic structure of the vector-control algorithm for the PMSM using FOC technique is shown in figure 3.

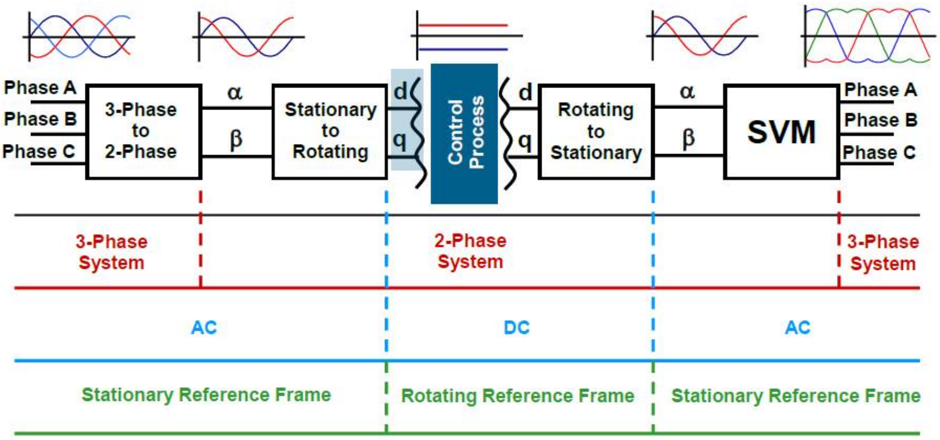

Fig. 3 FOC Transformations

To decompose the currents into torque-producing and flux-producing components, the rotor position should be kmown. This requires an accurate sensing of the rotor position and velocity information. The incremental encoders or resolvers attached to the rotor are mostly used as position transducers for vector-control drives. In some applications, the use of speed/position sensors is not required. The aim is not to measure the speed/position directly, but to employ some indirect techniques to estimate the rotor position instead. The algorithms that do not employ speed sensors are called “sensorless control”.

In the FOC techniques, it is able to control the field and torque of the motor separately. The aim of the control is to regulate motor speed. The speed command value is set by the high-level control. The algorithm is executed in two control loops. The fast inner control loop is executed with a period of 100 µs. The slow outer control loop is executed with a period of 1 ms.To achieve the goal of the PMSM control, the algorithm uses feedback signals. The essential feedback signals are the 3-phase stator current and DC-bus voltage. The regulator output is used for the stator voltage. To operate properly, the presented control structure requires either the position and speed sensors on the motor shaft or an advanced algorithm to estimate the position and speed. The fast control loop executes two independent current-control loops: the direct-axis current PI controllers which is used to control the rotor magnetizing flux and the quadrature-axis current PI controllers corresponds to the motor torque. The slow control loop executes the speed controller and lower-priority control tasks. The PI speed controller output sets a reference for the torque-producing quadrature-axis component of the stator current [10].

The space vector modulation (SVM) directly transforms the stator-voltage vectors from the 2-phase α, β-coordinate system into pulse width modulation (PWM) signals (duty-cycle values). The standard technique of output voltage generation uses the inverse Clarke transformation to obtain 3-phase values. The duty cycles needed to control the power stage switches are then calculated using the phase voltage values. Although this technique provides good results, space vector modulation is more straightforward (valid only for transformation from the α, β-coordinate system).SVM is a technique used as a direct bridge between the vector control (voltage space vector) and PWM. The SVM technique consists of these steps - Sector identification, Space voltage vector decomposition into directions of sector base vectors and PWM duty cycle calculation. The principle of SVM is the application of voltage vectors for certain instances in such way that the mean vectorof the PWM period TPWM is equal to the desired voltage vector.

B. Direct Torque Control Technique (DTC)

The Direct Torque Control technique was introduced by I. Takahashi and T. Noguchi in 1980’s for Induction motors as a new approach for torque and flux control [11]. The DTC directly controls the inverter states based on the errors between the references and estimated values of torque and flux. It selects one of the six voltage vectors generated by voltage source inverter to keep and flux within the limits of two hysteresis band. The characteristics of DTC are good dynamic torque response, robustness and low complexity [12]. The basic block diagram of the conventional DTC PMSM is shown in the figure 3. It includes current transform, torque and stator flux estimators, torque and flux hysteresis comparators, a switching table and a voltage source inverter. As in figure 3, only two input currents are sensed. The motor in a drive system is normally operated with its neutral point floating, so the current not sensed is obtained from the other two as mentioned in equation (5).

$$i_a + i_b + i_c = 0 \tag{5}$$

In the DTC system, variables are transformed in *dq* stator reference frame, which does not make use of any angular information. The current i_{qd}continues into the flux estimator into which enters the voltage$v_{qd}$from the voltage vector. The control action taken by the DTC control is based on the states of the flux and the torque hysteresis comparators. Flux is increased by applying a vector pointing in the flux direction and torque is increased by vector pointing in the rotational direction. In order to do this, the angular position of the stator flux vector must be known so that the DTC can chose between the appropriate set of vectors depending on the flux position. In order to calculate the torque value, one has to substitute the calculated fluxes and current values. From equation (4), we obtain the simplified form, as in equation (6).

$$T_e = \frac{3P}{4}\left(\lambda_d i_q + \lambda_q i_d\right) \tag{6}$$

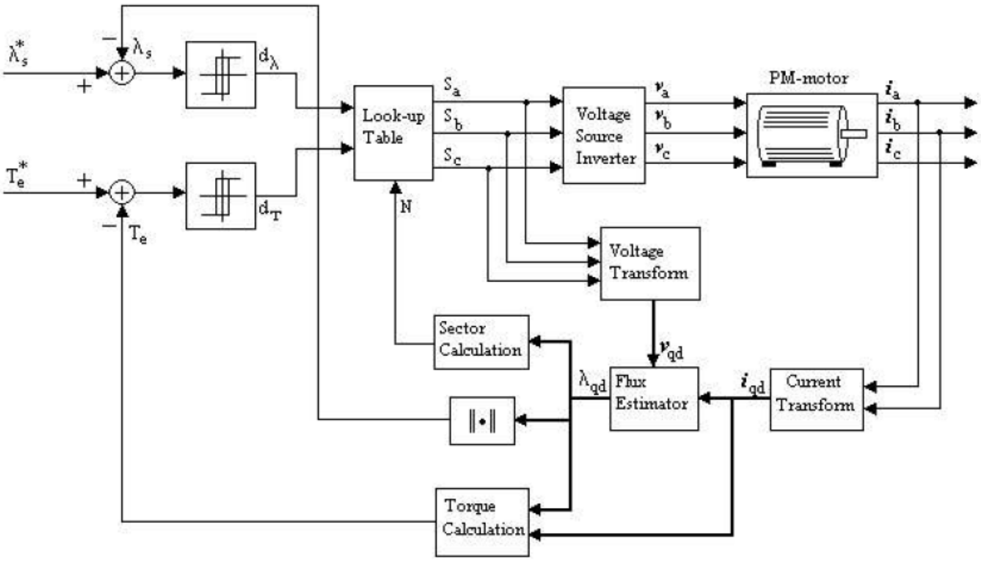

Fig. 4 Block Diagram of the conventional DTC

Table 1 Conventional DTC Look-up table

$K(\gamma_s)$		1	2	3	4	5	6
$d_\psi = 1$	$d_\Gamma = 1$	V2	V3	V4	V5	V6	V1
	$d_\Gamma = 0$	V7	V0	V7	V0	V7	V0
	$d_\Gamma = -1$	V6	V1	V2	V3	V4	V5
$d_\psi = -1$	$d_\Gamma = 1$	V3	V4	V5	V6	V1	V2
	$d_\Gamma = 0$	V0	V7	V0	V7	V0	V7
	$d_\Gamma = -1$	V5	V6	V1	V2	V3	V4

The estimated torque and flux values are compared to their command values. The difference between their command and estimated value is compared in the hysteresis comparators. The hysteresis comparator states together with the sector number are used by the Look up table to choose an appropriate voltage vector. A high hysteresis state increases the corresponding quantity and vice versa. The voltage vector selected is sent to the voltage source inverter which synthesizes it [13].

IV. RESULTS AND DISCUSSIONS

In the table 2, the control methods of PMSM are summarised under certain basic indices. As per the summary mentioned in the below table, it is understood that following the direct torque control technique is very simpler and better when compared with the directed flux control or the field oriented control technique. Even though both DTC and FOC come under the vector control group, they have external differences [14]. Thus, the comparison of FOC and DTC techniques of PMSM were studied.

Table 2 Comparison of FOC and DTC

	FOC	DTC
System Transformation	Need	No need
Voltage Modulation	Need	No need
Sensitivity to parameter changes	Big	Average
Sensor position	Need	No need
Regulators	3 stator regulators (Hysteresis)	Torque and Flux Regulator

V. CONCLUSION

In this paper, a study has been done on the main characteristics of the two common vector control methods – FOC and DTC of PMSM. The advantages, disadvantages and the principle of operation of both the control schemes were studied and compared. It can be analysed that both the methods provide a good performance response, with quicker torque dynamics in the case of DTC and better steady-state behaviour in case of FOC. Depending on the requirements of an application one method can be more convenient than the other.

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