Field Oriented Control Principles for Synchronous Motor

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***Abstract*—AC motors are more rugged and have much simpler construction as compare to DC motors and after introducing field oriented control, it has been made possible for the AC motors to achieve high dynamic performance similar to DC motors. This paper focus on the discussion about vector control principles and how it solved the problems of controlling AC motors, particularly synchronous machine such as decoupling control of torque and speed. Starting with the brief history about the evolution of motor drives then discuss about the significance of FOC including mechanism of torque production in synchronous motor, importance of phase transformation and advancing it to a simplified DQ model of PM synchronous motor. Finally combining altogether to elaborate the proposed model of complete FOC drive system. This paper adopted a different approach to describe these concepts in a lucid manner that many literatures lacking.**

***Index Terms*— field oriented control, vector control, AC drives, DQ modelling, synchronous motor**

I. Introduction

During past century, we have seen tremendous innovations and improvements in the field of machine and control engineering. More and more innovative electrical machines have been developed because current situation of economy and environment insists upon smart utilization of materials and efficient use of energy resources [1], [2]. For this reason the control systems has always been a key issue since they influence drastically the overall system performances. Development of control systems starts from analog design. Those systems were based on power amplifiers. Then, Vacuum tubes based electronic circuits were used for power electronics and controllers. Then the invention of transistor and silicon controlled rectifier (SCR) revolutionized the power electronics industries. Those solid state control systems and electrical drives are lot cheaper, higher in performance and having numerous improvements. Then control system taken the advantages of computing technology from the early 80’s. Starting with simple microprocessor, they moved to microcontrollers and then to digital signal processors (DSPs) and they integrated machines more and more with the outside environment using special sensors. The recent evolution was based on the design of specific processors for motion control [3], [4].

With the increasing complexity of control systems, mechanical constructions of electrical machines has been simplified remarkably. In the beginning DC motors were used in industries worldwide. Its mechanical construction is much complicated mainly due to internal mechanical commutation system. With the development of power semiconductors and integrated circuits, more complex drives were made with electronic commutation system, it was made practical to use much simplified and robust brushless motor structures like synchronous and induction AC motors. Later on Switched Reluctance Motor (SRM) and Flux Switching Motor (FSM).

Beside the role of control processors, control principles play a key role for the overall performance of the motors and reliability of electronic components. In most of the modern digital drive system, two key variables, flux and torque have to be controlled. Field oriented control system effectively perform this task. It was introduced in the early 70s in Germany, It has been widely adopted in many industries by the end of the 90s since it allows AC electrical machines to have good transient performances in terms of torque and speed [4].

II. Significance of Field Oriented Control (FOC) in AC Motor Drives

In the dc machine, the field current in the stationary poles producing the magnetizing flux and the armature current directly controlling the torque are independently accessible. Moreover, for a fully compensated dc motor, the spatial angle between the flux and the armature mmf is held at 90 ° with respect to each other, independent of the load, by the commutator and the brushes whereas in an ac motor (both induction and synchronous motor), the spatial angle between the rotating stator and rotor fields varies with the load and gives rise to oscillatory dynamic response. Control methods for ac motors that emulate the dc motor control by orienting the stator current so that spatial angle between rotor and stator flux can be maintain at 90o in this way this technic attain independent and 'decoupled' control of flux and torque are known as 'field orientation' control (FOC) [5]. It was introduced in the early 1970s. For implementing FOC, a position sensor is needed for constantly monitoring the rotor position. It was introduced by Blaschke [6]. It require control of both the magnitude and phase of ac quantities and thus are referred to as 'vector control methods'. . Now, it has been established as a powerful

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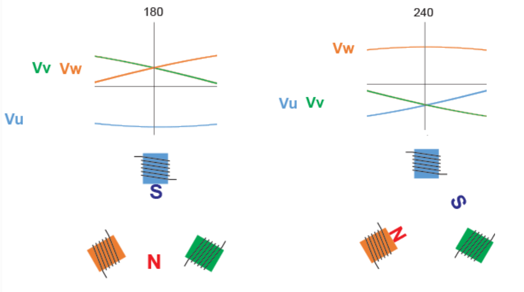
technique in the field of ac motor drives and adopted worldwide [6], [7].

A. *Torque production in Synchronous Motor*

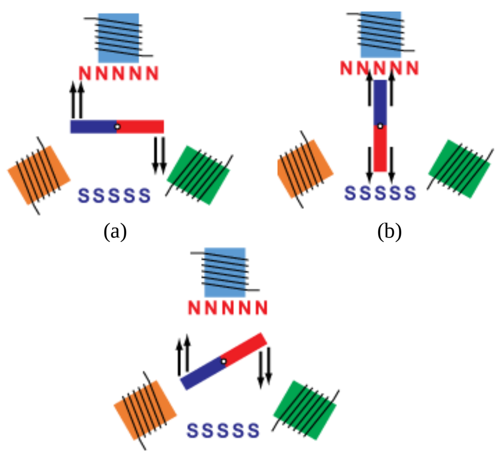
To understand the mechanism underlying the principle of FOC we have how Synchronous motor produces maximum torque. In synchronous motor, stator coils are energized with three phase current having phase difference at 120^o. In this way stator experiences a rotating magnetic field. As illustrated in fig 1.1, in three phase system, at 180^o, V and W phases are in half way of their peak positive voltages and U phase is in its peak negative, so north pole field is due to combination of V and W coils and south pole is due to U coil. In the similar way at 240^o, phase polarities will be changed as shown in fig 1.2, and magnetic field will be rotate about 45^o clockwise. Stator magnetic field will rotate further with the supply of three phase current.



(a) (b)

Figure 1. Rotating stator magnetic field due to three phase AC current

Now consider that the rotor consist of a magnet. Its north and south poles will be attracted towards south and north poles of stator field respectively. As shown in fig 2, torque will be maximum when rotor field is 90^o apart from stator field and minimum torque will be experienced at 0^o, similarly at other alignments, there will be some torque between its maximum and minimum value [8]-[10].



(a) (b)

(c)

Figure 2. Effect of angle between rotor and stator fields on torque production. (a) Maximum Torque (b) Minimum Torque (c) Non-optimal Torque

B. *Orientation of Stator Field through FOC*

Therefore, for driving the motor at full torque, it is essential to constantly monitor the rotor angular position, then alter the three phase voltage in a way that armature mmf always remain 90o apart from rotor flux. This procedure of FOC would be very simple and straight forward by simply measuring the angular position of rotor and add 90 in it for the calculation of three phase voltages using equations (1), (2) and (3) for producing 900 out of phase magnetic field.

$$V_u = V_m \sin\theta \tag{1}$$

$$V_v = V_m (\sin\theta - 120^o) \tag{2}$$

$$V_w = V_m (\sin\theta - 240^o) \tag{3}$$

But it is impractical because in AC circuits, current is not always in phase with the voltage. It is shown in fig.3. Since stator magnetic field establishes due to AC current. Current phase leads or lags voltage in AC circuits due to number of factors such as EMF, inductance and loads.

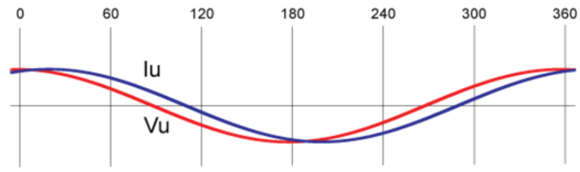
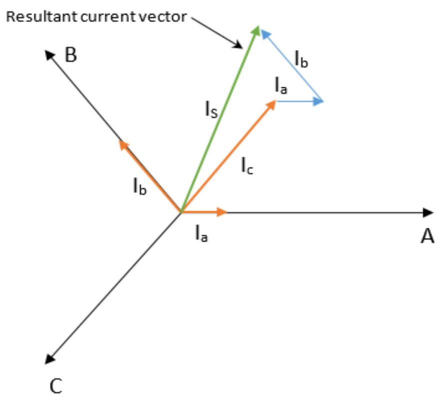
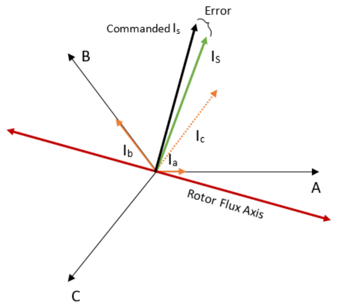


Figure 3. Phase difference of current vs voltage with respect to rotor position

Since direction of stator field depends upon the resultant of three current phases. It is represented in terms of vectors in Fig. 4(a). This resultant current vector "Is" should be oriented 90o with respect to rotor flux direction for maximum pull. Direction of "Is" can be controlled by adjusting the magnitude of phase currents. During rotation, rotor flux direction changes continuously. The control algorithm should monitor the new rotor position continuously due to which Is become misaligned with the new rotor direction and controller should adjust the magnitude of phase current Iu, Iv and Iw to again align "Is" orthogonally upon the rotor flux as shown in Fig. 4(b) [8], [11].



(a)



(b)

Figure 4. (a) Vector representation of stator current. (b) Aligning current vector orthogonal to rotor axis

C. Simplification of FOC through Parameter Phase Transformation

Altering the fast changing values of AC parameters to align the stator field require sophisticated algorithms and high end processors, which is not recommended for such high speed motor application. For reducing the complexity by transforming the AC parameters into DC, two transformations are very popular known as Clarke and Park transformations.

1) Clarke and park transformation

Clarke transformation translate the three phase variables from three axis reference frame into two axis orthogonal stationery frame as shown in Fig. 5(a) and 5(b) respectively. It is also known as αβ transformation.

Park Transformation was initially proposed by Robert H. Park in 1929. It is also known as dq transformation. It is use to reduce three phase AC quantities into two phase DC quantities through transformation of three axis stationary frame into rotating two axis rotating frame as shown in Fig. 5(c). Park transformation much simplified the FOC operation by introducing a rotating frame of reference which rotates along rotor flux axis. In this way q and d current components are constant in rotor frame. Its direct component of current Id is parallel to rotor flux direction and quadrature component Iq is perpendicular to it. By simply keeping Id zero and let Iq to develop the mmf field in the stator, maximum torque can be achieved. [11], [12].

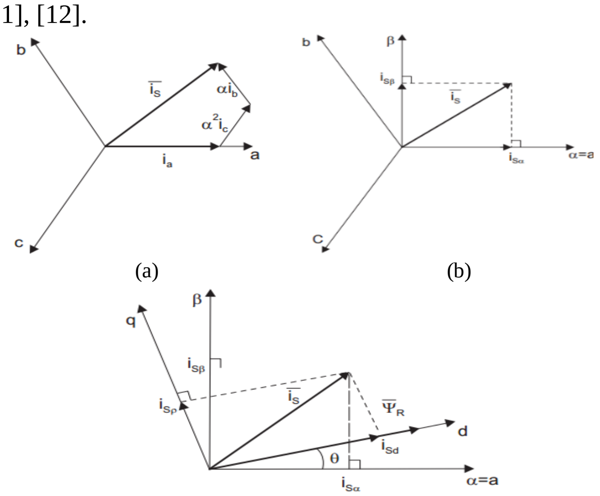


Figure 5. (a) Three axis reference frame. (b) Two axis αβ stationary frame. (c)Two axis dq rotating frame.

$$\begin{bmatrix} I_\alpha \\ I_\beta \\ I_\gamma \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix}\begin{bmatrix} I_\alpha \\ I_\beta \\ I_\gamma \end{bmatrix} \tag{5}$$

where,
Va, Vb, Vc are three-phase quantities
Vα, Vβ are the orthogonal stationary reference frame quantities

Park and Inverse Park transformation is given in equation 6 and 7 respectively

$$\begin{bmatrix} V_q \\ V_d \\ V_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r - 120) & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \\ V_0 \end{bmatrix} \tag{7}$$

where,
Va, Vb, Vc are three-phase quantities
Vd, Vq are the orthogonal rotatory reference frame quantities

III. DQ MODEL OF PM SYNCHRONOUS MOTOR

For implementing FOC in Simulink or other simulation environment, we need to transform the Synchronous motor's three phase model into dq model for reducing the complexity of modelling and for performing simulation in real time.

The DQ model of PM Synchronous Motor shown in Fig. 6 is based on the assumption that d-axis is parallel to the rotor flux and q-axis is perpendicular to d-axis. Rotating d-axis makes an angle θr with a-axis which is fixed to the stator. [13]

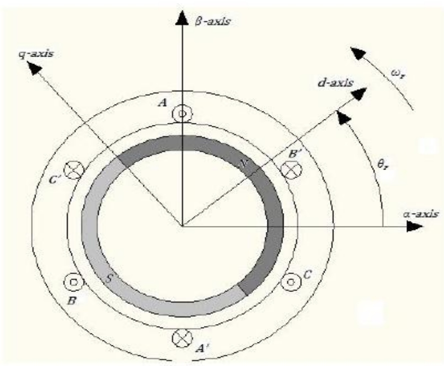


Figure 6. DQ axis of Synchronous Motor model

Following equations yields after DQ transformation of synchronous motor model [13], [14].

DQ transformed voltages are given by:

$$V_q = R_s i_q + \omega r \lambda d + \rho \lambda_q \tag{8}$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \tag{9}$$

Flux Linkages are given by:

$$\lambda_q = L_q I_q \tag{10}$$
$$\lambda_d = L_d I_d + \lambda_f \tag{11}$$

Substituting equations 3.3 and 3.4 into 3.1 and 3.2

$$V_q = R_s i_q + \omega_r (L_d\, i_d + \lambda_f) + \rho L_q i_q \tag{12}$$
$$V_d = R_s i_d - \omega_r L_q\, i_q + \rho (L_d i_d + \lambda_f) \tag{13}$$

Arranging equations 3.5 and 3.6 in matrix form

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{bmatrix} \begin{bmatrix} I_q \\ I_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{bmatrix} \tag{14}$$

The developed torque motor is being given by

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_d i_q - \lambda_q i_d\right) \tag{15}$$

The mechanical Torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \tag{16}$$

Solving for the rotor mechanical speed form equation 3.9

$$\omega_m = \int \left(\frac{T_e - T_l - B\omega_m}{J}\right) dt \tag{17}$$

And

$$\omega_m = \omega_r \left(\frac{2}{P}\right) \tag{18}$$

In the above equations ωr is the rotor electrical speed where as ω_m is the rotor mechanical speed.

A. *Equivalent Circuit Based on DQ Model of Synchronous Motor*

Equivalent circuit of PM Synchronous motor that will be used for simulation modelling is derived from equations (8) and 9. [14].

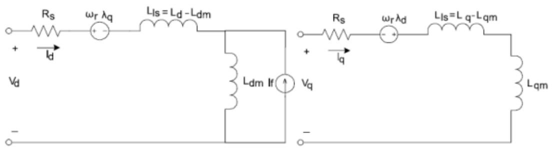


Figure 7. D-Q Equivalent Circuit of PM Synchronous Motor

IV. Complete Model of FOC Drive System

Proposed field oriented control of synchronous motor is represented in the block diagram shown in Fig. 8. It is based on the equations (8) to (18) and DQ equivalent circuit of synchronous motor shown in Fig. 8.

Speed and angle estimator calculate the angle and speed from the feedback given by position sensor. Purpose of ADC block is to digitally sampling three phase analog current quantities. Through Park transformation, three phase current further convert into dq parameters. Estimated motor speed is differentiate with the desired speed. Then it is send to PID controller. Its purpose is to generate torque commands based on the speed differences. Then Torque to Iq block convert torque into quadrature current Iq using equation 3.8.

Furthermore reference Id is set to zero to achieve maximum torque. Calculated Id from Park transformation block is differentiate with the reference Id and send to another PID controller. Reference Iq and Id is converted into reference Iabc through inverse Park transformation. A PWM generator convert them into vector space PWM signals which is finally fed into a current controlled inverter to generate required three phase voltage to power the motor. [13]-[16]

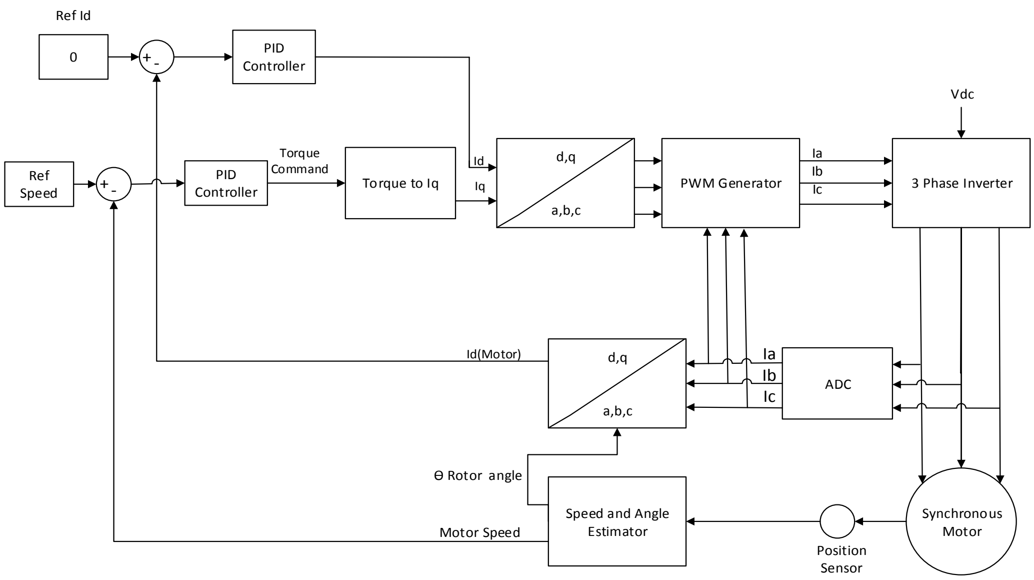


Figure 8. Block Diagram of Field Oriented Control of Synchronous Motor

V. CONCLUSION

Field Oriented Control is a powerful control mechanism to orient the stator field for the decoupling control of torque and speed like DC motors and due to phase transformation, its complexity reduced a lot. Now FOC can be easily implemented on low cost microcontrollers and DSPs. In many industrial applications DC motors replaced with more reliable and low cost brushless AC motors. The proposed FOC model of PM synchronous motor is simplified and optimized enough to be implemented in a microcontroller. it is suitable for low cost house hold applications. Future consideration is to simulate the model in MATLAB/Simulink and then produce a prototype drive.

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