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Vector Control of Permanent Magnet Synchronous Motor Based On Sinusoidal Pulse Width Modulated Inverter with Proportional Integral Controller

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ABSTRACT
This paper is concerned with vector control of permanent magnet synchronous motor (PMSM). The mathematical model of PMSM, using the powerful simulation modeling capabilities of Matlab/Simulink is implemented. The entire PMSM control system is divided into several independent functional modules such as PMSM body module, inverter module and coordinate transformation module and Sinusoidal pulse width modulation (SPWM) production module and so on. we can analyzed a variety of simulation waveforms and it provide an effective means for the analysis and design of the PMSM control system.
Keywords **-** Clarke Transformation, Mathematical model of Permanent magnet synchronous motor, Park Transformation, Sinusoidal pulse width modulation, Vector control.

I. INTRODUCTION

Compared with other forms of motor, Permanent magnet synchronous motor (PMSM) has better dynamic performance, smaller size and higher efficiency. In recent years, with the rapid development of electric power electronics technical, rare earth permanent magnetic materials and the increasingly sophisticated research in Permanent magnet motor. PMSM is widely used in national defense, agriculture and daily life [1]. PMSM is a multivariable, nonlinear and high coupling system. The output torque and stator current present a complicated function relation. Magnetic field can be decoupled to get a good control performance. It was no slip frequency current, less affected by the rotor parameters, easier to implement vector control [2]. Therefore, the model of PMSM vector control has become a widespread concern. The analysis of mathematical model of PMSM, with the powerful simulation modeling capabilities of Matlab/Simulink, the PMSM control system will be divided into several independent functional modules such as PMSM motor module, inverter module, coordinate transformation module and SPWM production module and so on. By combining these modules, the simulation model of PMSM control system can be built.

II. CLARKE AND PARK TRANSFORMATION

Three phase ac machines conventionally use phase variable notation. For a balanced three phase, star connected machine

$f_a+f_b+f_c=0$

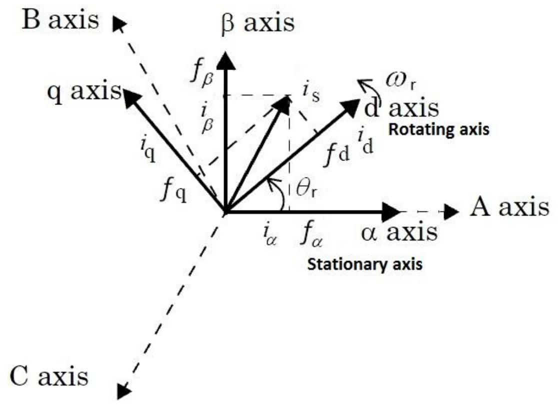

Fig.1. Current space vector in stationary and rotating reference frame

Where f_a, f_b and f_c denote any one of current, voltage and flux linkage [3]. The transformation from three-phase to two-phase quantities can be written in matrix form as:

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = 2/3 \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (1)$$

Where f_α and f_β are orthogonal space phasor. The stator current space vector is defined as the complex quantity:

$$i_s = i_\alpha + \boldsymbol{j} i_\beta \quad (2)$$

It is possible to write (2) more compactly as:

$$i_s = 2/3(i_a + \boldsymbol{a} i_b + \boldsymbol{a}^2 i_c) \quad (3)$$

Where i_a, i_b and i_c are instantaneous phase currents and $\boldsymbol{a}$ is a vector operator that produces a vector rotation of = $(2\pi)/3$. The choice of the constant in the transformation of equation (1) is somewhat arbitrary [4], [5]. Here, the value of 2/3 is chosen. Its main advantage is that magnitudes are preserved across the transformation. The inverse relationship is written as:

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} \quad (4)$$

Transformation equations (1) and (4) are known as the Forward Clarke Transformation and Reverse Clarke Transformation respectively. Now if we transform the stator variables from stationary reference frame to rotating reference frame then we write in matrix form as:

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} \quad (5)$$

Where θr is the angle between stationary reference frame and rotating reference frame is shown in Fig.1. Transformation equation (5) is known as Park transformation.

III. MATHEMATICAL MODEL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

The mathematical model is similar to that of the wound rotor synchronous motor. Since there is no external source connected to the rotor side and variation in the rotor flux with respect to time is negligible, there is no need to include the rotor voltage equations. Rotor reference frame is used to derive the model of the PMSM [6], [7].

The electrical dynamic equation in terms of phase variables can be written as:

$$v_a = R_a i_a + p\lambda_a$$
$$v_b = R_b i_b + p\lambda_b$$
$$v_c = R_c i_c + p\lambda_c \quad (6)$$

While the flux linkage equations are:

$$\lambda_a = L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + \lambda_{ma}$$
$$\lambda_b = L_{ab} i_a + L_{bb} i_b + L_{bc} i_c + \lambda_{mb}$$
$$\lambda_c = L_{ac} i_a + L_{bc} i_b + L_{cc} i_c + \lambda_{mc} \quad (7)$$

Considering symmetry of mutual inductances such as $L_{ab} = L_{ba}$, self inductances $L_{aa} = L_{bb} = L_{cc}$ and flux linkage $\lambda_{ma} = \lambda_{mb} = \lambda_{mc} = \lambda_m$. Applying the transformations (1) and (5) to voltages, flux linkages and currents from equation (6)-(7), we get a set of simple transformed equations as:

$$v_q = (R_s + L_q p)i_q + \omega_r L_d i_d + \omega_r \lambda_m$$
$$v_d = (R_s + L_d p)i_d - \omega_r L_q i_q \quad (8)$$

L_d and L_q are called d and q-axis synchronous inductances, respectively. ω_r is motor electrical speed. Each inductance is made up of self inductance (which includes leakage inductance) and contributions from other two phase currents.

The electromagnetic torque T_e can be represented as:

$$T_e = (3/2)(P/2)(\lambda_m i_q + (L_d - L_q) i_d i_q) \quad (9)$$

It is apparent from the above equation that the produced torque is composed of two distinct mechanisms. The first term corresponds to the mutual reaction torque occurring between i_q and the permanent magnet, while the second term corresponds to the reluctance torque due to the differences in d axis and q-axis reluctance (or inductance). The equation for motor dynamics is:

$$T_e = Jp\omega_r + B\omega_r + T_l \quad (10)$$

IV. VECTOR CONTROL

Vector control is also known as decoupling or field orientated control. Vector control decouples three phase stator current into two phase d-q axis current, one producing flux and other producing torque. This allows direct control of flux and torque. So by using vector control, the PMSM is equivalent into a separately excited dc machine. The model of PMSM is nonlinear. So by using vector control, the model of PMSM is linear.

The scheme of vector control is based on coordinate transformation and motor torque equation by means of controlling stator current to improve the performances of motor, and is widely used in the field of PMSM servo system. In the control of a three-phase PMSM system, modulated current is supplied to the A-B-C stator windings to build rotated magnetic field and drive the rotator. The vector control strategy is formulated in the synchronously rotating reference frame. By Clarke–Park transformations and inverse transformations the equivalent relations of currents are built among a.b,c stator coordinates, stationary α, β axis coordinates and rotating d, q axis coordinates.

Fig.2. shows a vector diagram of the PMSM. Phase a is assumed to be the reference. The instantaneous position of the rotor (and hence rotor flux) is at θr from phase a. The application of vector control, so as to make it similar to a DC machine, demands that the quadrature axis current i_q be in quadrature to the rotor flux. Consequently i_d has to be along the rotor flux since in the reference used i_d lags i_q by 90°. If i_d is in the same direction as the rotor flux, the d axis stator flux adds to the rotor flux that leads to increase in the net air gap flux. On the other hand if i_d is negative then the stator d-axis flux is in opposite to that of the rotor flux resulting in a decrease in air gap flux.

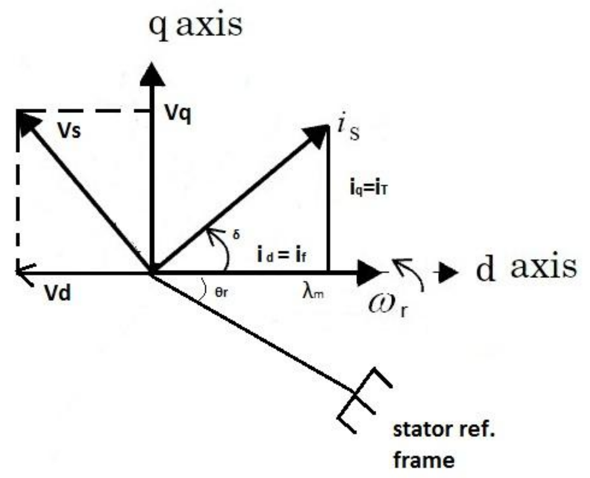

Fig.2. Phasor diagram of PMSM

The PMSMs are designed such that the rotor magnet alone is capable of producing the required air gap flux up to the rated speed. Hence i_d is normally zero in the constant torque mode of operation. Consider three phase currents are:

$i_a = i_s \sin(\omega_r t + \delta)$
$i_b = i_s \sin(\omega_r t + \delta - \frac{2\pi}{3})$
$i_c = i_s \sin(\omega_r t + \delta + \frac{2\pi}{3})$ (11)

Where $\theta_r = \omega_r t$, from phasor diagram we get:

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = i_s \begin{bmatrix} \sin\delta \\ \cos\delta \end{bmatrix} \quad (12)$$

i_q = Torque-producing component of stator current = i_T
i_d = Flux-producing component of stator current = i_f
If we make id = 0 by δ = 90º then the electric torque equation (9) becomes:

$$T_e = (3/2)(P/2)\,\lambda_m i_q \quad (13)$$

Hence the electric torque depends only on the quadrature axis current and a constant torque is obtainable by ensuring that i_q is constant. The constant air gap flux required up to rated speed. Vector control is therefore only possible when precise knowledge of the instantaneous rotor flux is available. Hence it is inherently easier in the PMSM than in the induction motor because the position of the rotor flux is uniquely determined by that of the rotor position in the PMSM. Hence with the application of vector control, independent control of the torque (i_q) and flux (i_d) producing currents are possible.

V. SINUSOIDAL PWM

Fig.3. shows circuit model of three phase PWM inverter and Fig.4. shows waveforms of carrier signal (V_{tri}) and control signal ($V_{control}$), inverter output line to neutral voltages are V_{AO}, V_{BO}, V_{CO}, inverter output line to line voltages are V_{AB}, V_{BC}, V_{CA} respectively.

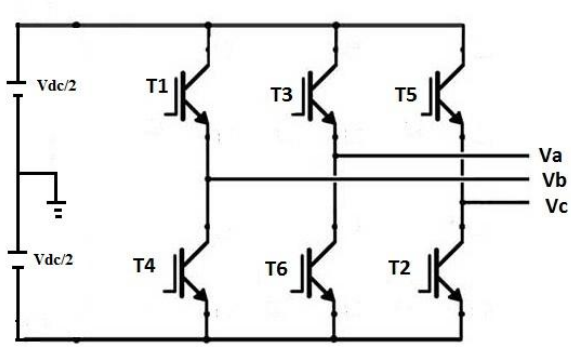

Fig.3. Three phase PWM inverter

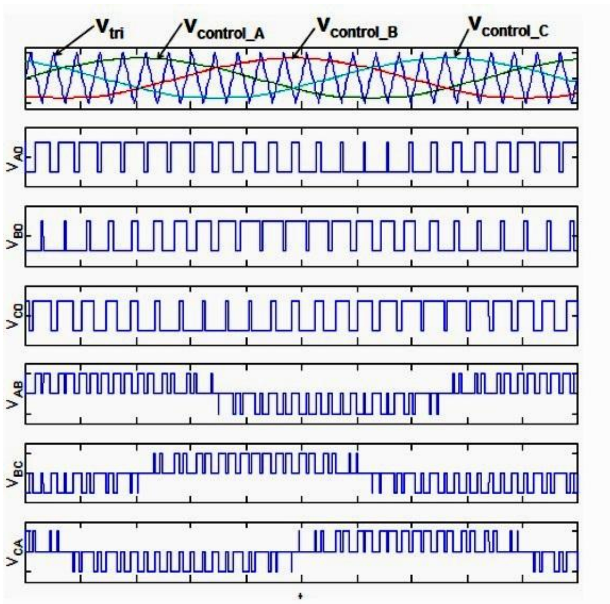

Fig.4. Waveforms of three phase sinusoidal PWM inverter

The inverter output voltages are determined as follows:

When $V_{control} > V_{tri}$, $V_{AO} = V_{DC}/2$
When $V_{control} < V_{tri}$, $V_{AO} = -V_{DC}/2$
Where $V_{AB} = V_{AO}-V_{BO}$, $V_{BC} = V_{BO}-V_{CO}$, $V_{CA} = V_{CO}-V_{AO}$.

VI. SIMULATION MODEL OF PMSM

Fig.5. is a model for vector control of PMSM.

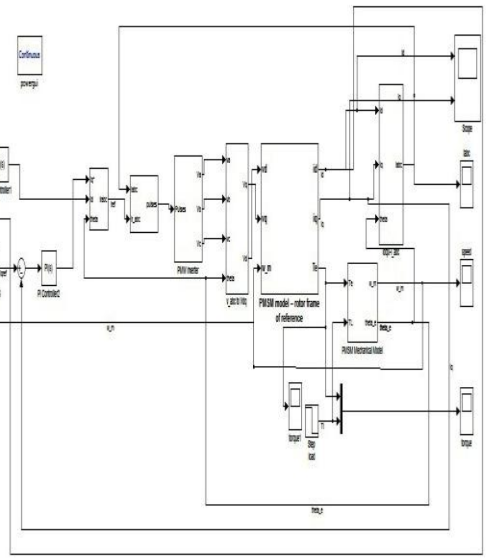

Fig.5. Simulation model for Vector control of PMSM

VII. SIMULATION RESULTS

According to the proposed vector control of PMSM simulation model, run in MATLAB, using the motor parameters are as follows: electrical power P = 2Kw, DC voltage V_{dc} = 700V, Stator winding resistance R_s = 1.4Ω, d axis winding inductance L_d = 0.0066H, q axis winding inductance L_q = 0.0058H, the rotor magnetic flux λ_m = 0.1546Wb, moment of inertia J = 0.00176Kg*m^2, the pole number P = 6, magnetic flux density B = 0.00038818Wb/m^2, reference speed = 1200rpm. Set the total simulation time t = 0.2s.

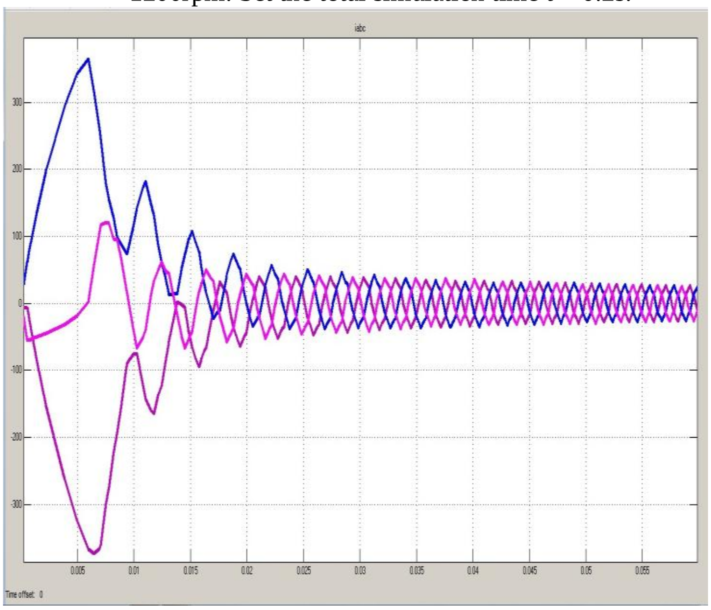

Fig.6. Current response curve

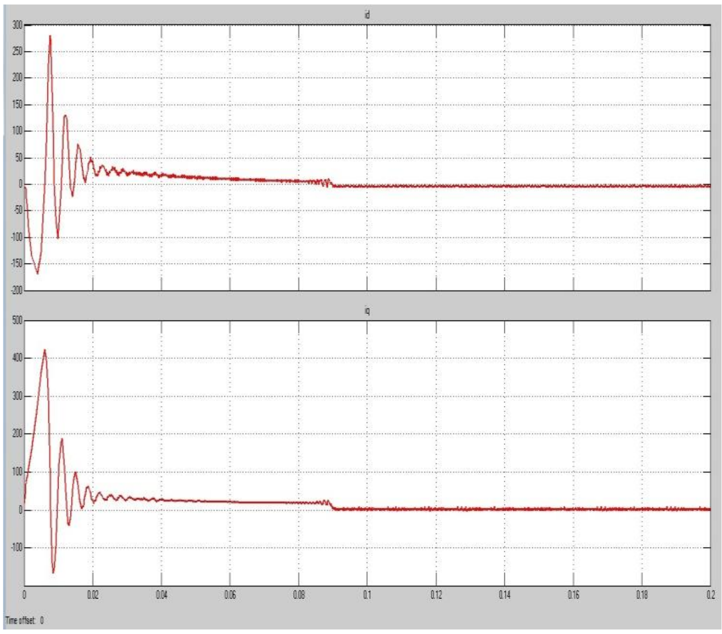

Fig.7. dq axis current waveform

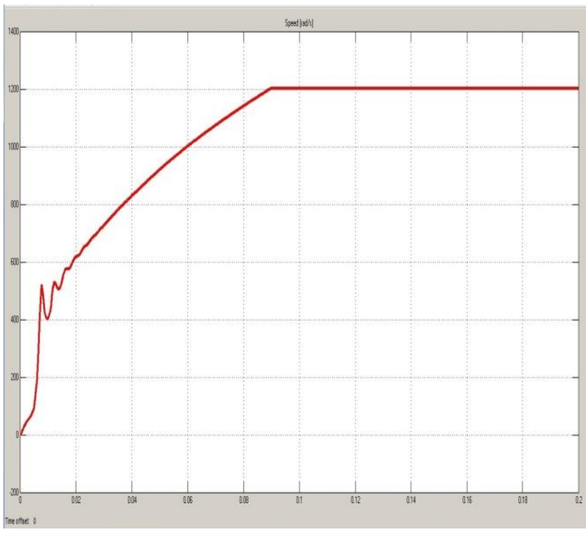

Fig.8. Speed response curve

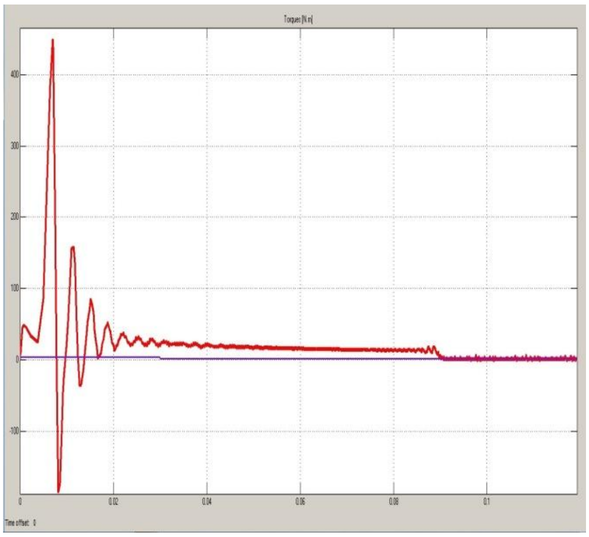

Fig.9. Electromagnetic torque waveform

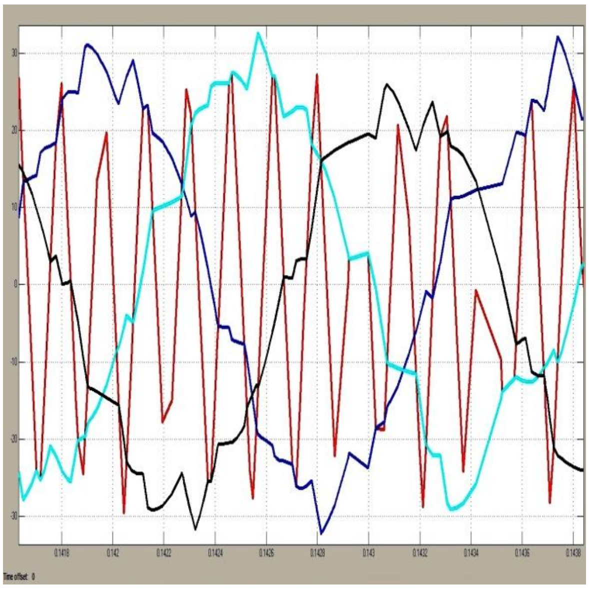

Fig.10. Pulse width modulation

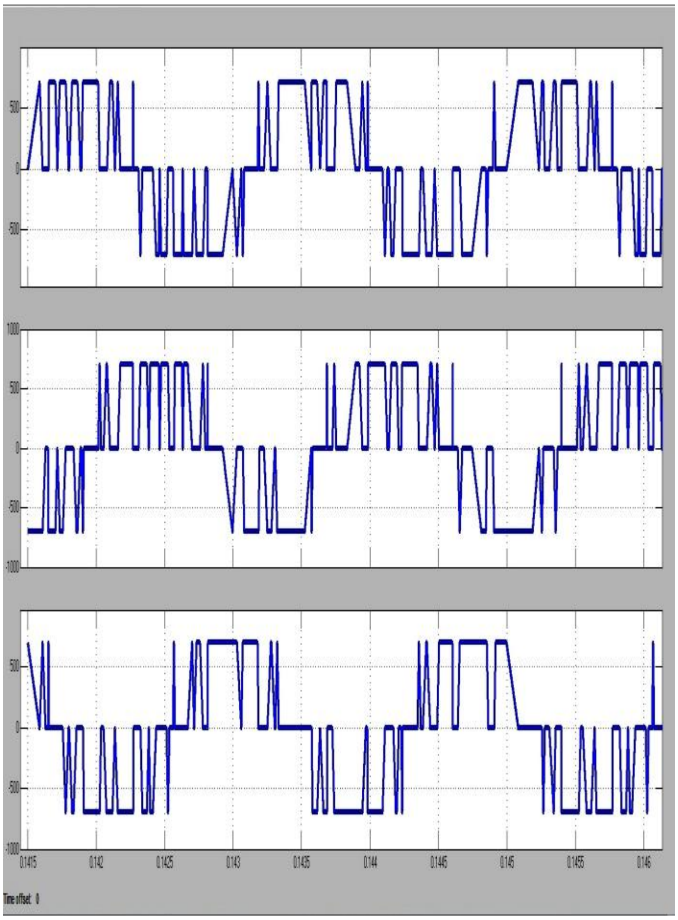

Fig.11. Inverter output voltage waveform

VIII. CONCLUSION

In this paper vector control has been described in adequate detail and has been implemented on PMSM in real time. The time varying abc currents are made stationary using Reverse Park Transformation, to simplify the calculation of PI controller's constants. This method enables the operation of the drive at zero direct axis stator current. Therefore, it permits the operation at minimum armature current. In this situation, we obtain maximum torque per ampere as well as maximum efficiency. The motor needs much smaller voltage compared to the conventional synchronous motor. This leads to designing a voltage source inverter with lower voltage and current ratings. This voltage source inverter, together with its small size, will reflect a total low cost. The performance of vector control is quite satisfactory for achieving fast reversal of PMSM even at very high speed ranges.

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