Vector control of asymmetrical six-phase synchronous motor

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Abstract: Vector control scheme has been well adopted for higher performance applications of AC motor. Therefore, this paper presents an extensive development and investigation of vector control scheme for asymmetrical six-phase synchronous motor in a new two-axis (M–T) coordinate system. Phasor diagram has also been developed in a simplified way, followed by its implementation technique. Analytical results have been presented for four-quadrant operation of synchronous motor, employing the developed vector control scheme. In analytical control model, common mutual leakage reactance between the two winding sets occupying same stator slot has been considered.

1. Introduction

The multiphase (more than three phase) AC motor drives are used as a substitute of conventional three-phase motor in different applications particularly, in propulsion system of ship and vehicle, textile and steel industries, rolling mills, power plants, etc. This is because it offers certain potential advantages when compared with its three-phase counterpart, like reduction in space and time harmonics, reduced torque pulsation, increased power handling capability, higher reliability, etc. (Levi, 2008; Singh, 2002).

Field-oriented control (i.e. vector control) technique has been widely used in high performance of AC motor drives. In this regard, an abundant number of literatures are available for three-phase motor (Bose, 2002; Das & Chattopadhyay, 1997; Jain & Ranganathan, 2011; Krause, Waszynskzuk, & Sudhoff, 2004), but a few for six-phase induction motor (Bojoi, Lazzari, Profumo, & Tenconi, 2003; Singh, Nam, & Lim, 2005), wherein d–q model of machine has been used in synchronously rotating
reference frame. But the utilization of this scheme has not been reported for field excited six-phase synchronous motor. Therefore, the paper is dedicated to explore and develop the control technique for asymmetrical six-phase synchronous motor. In the control scheme, a new two axis (M–T coordinate) has been introduced along which the decoupled control of flux and torque is achieved. Following the inclusion of control technique, a detailed analytical results have been presented for motor operation in four quadrants.

2. Mathematical modeling

For the purpose of realizing the six-phase motor, it is a common practice to split the existing three-phase stator winding into two, namely a b c and a’b’c’. Both splitted stator winding sets (a b c and a’b’c’) are physically displaced 30° apart to realize asymmetrical six-phase winding configuration. Asymmetrical six-phase winding configuration yields the reduced torque pulsation (Singh, 2002, 2011) due to the elimination of lower order harmonics. On the rotor side, it is equipped with field winding $f_r$ together with the damper windings $K_d$ and $K_q$ along $d$ and $q$-axis, respectively.

The equation of the motor can be written using machine variables. But this will yield a set of non-linear differential equations. Nonlinearity is due to the existence of inductance term which is time varying in nature. Such equations are computationally complex and time-consuming. Therefore, to simplify the motor equations with constant inductance term, it will be conveniently written in rotor reference frame using Park’s variables (Iqbal, Singh, & Pant, 2014, in press; Schiferl & Ong, 1983; Singh, 2011).

$$v_{dqk} = r_{sk} i_{dqk} + \frac{\alpha_s}{\omega_b} \psi_{dqk} + \frac{p}{\alpha_b} \psi_{dqk}$$

(1)

$$v_{dqr} = r_{dq} i_{dqk} + \frac{p}{\alpha_b} \psi_{dqr}$$

(2)

$$v_{dqk} = \begin{bmatrix} v_{dk} & v_{qk} \end{bmatrix}^T$$

(3)

$$\psi_{dqk} = \begin{bmatrix} \psi_{dk} & -\psi_{qk} \end{bmatrix}^T$$

(4)

$$r_{dqk} = \begin{bmatrix} r_{dk} & r_{qk} \end{bmatrix}^T$$

(5)

for $k = \begin{cases} 1, & \text{for winding set a b c} \\ 2, & \text{for winding set a’b’c’} \end{cases}$

$$v_{dqr} = \begin{bmatrix} v_{Kd} & v_{Kq} & v_{fr} \end{bmatrix}^T$$

(6)

$$\psi_{dqr} = \begin{bmatrix} \psi_{Kd} & \psi_{Kq} & \psi_{fr} \end{bmatrix}^T$$

(7)

$$r_{dqk} = \begin{bmatrix} r_{Kd} & r_{Kq} & r_{fr} \end{bmatrix}^T$$

(8)

Equations of motor flux linkage per second may be conveniently written as the function of currents,

$$\psi = xi$$

(9)
where \(i = \begin{bmatrix} i_{djk} & i_{djk} \end{bmatrix}^T, \psi = \begin{bmatrix} \psi_{djk} & \psi_{djk} \end{bmatrix}^T\)

\(x\) is defined in Appendix 1.

The developed motor torque is expressed as

\[ \tau_e = \tau_{e1} + \tau_{e2} \tag{11} \]

where \(\tau_{e1}\) and \(\tau_{e2}\) are the developed motor torque associated with winding sets \(a\ b\ c\) and \(a'b'c'\), respectively, and expressed as

\[ \tau_{e1} = c(i_{q1}\psi_{d1} - i_{d1}\psi_{q1}) \tag{12} \]

\[ \tau_{e2} = c(i_{q2}\psi_{d2} - i_{d2}\psi_{q2}) \tag{13} \]

with \(c = \frac{3\ P\ 1}{2\ P_a}\)

The rotor dynamics having \(P\) number of poles is expressed as

\[ \frac{\omega_r}{\omega_b} = \frac{1}{P} \left[ \frac{1}{\omega_b} \frac{1}{2} \int (\tau_e - \tau_l) \right] \tag{14} \]

wherein, \(\tau_l\) is the load torque, \(p\) represents the derivative function w.r.t. time and all symbols stand to their usual meaning (Iqbal et al., in press). Evaluation of motor parameters is determined from the standard test procedure (Aghamohammadi & Pourgholi, 2008; Alger, 1970; Jones, 1967).

3. Vector control scheme

The operating performance of vector-controlled motor is greatly improved and similar to that of a separately excited DC motor (Bose, 2002). This is because of decoupled control of both flux component and torque component of stator current. The inclusion of vector control scheme is not similar to that of induction motor drive. The main difference lies on the fact that the air gap flux is attributed by both stator flux as well as field flux. Therefore, the resultant air gap flux will align along the axis which is different from conventional \(d\)-axis. Hence, a new \((M-T)\) coordinate axis has been introduced wherein, the resultant flux vector and torque current component will align along \(M\) and \(T\) axis, respectively. Machine variables in newly defined coordinate axis \((M-T)\) may be readily transformed to its equivalent \(d-q\) or vice versa by relation

\[ \begin{bmatrix} M_k \\ T_k \end{bmatrix} = \begin{bmatrix} \cos\delta_k & -\sin\delta_k \\ \sin\delta_k & \cos\delta_k \end{bmatrix} \begin{bmatrix} d_k \\ q_k \end{bmatrix} \tag{15} \]

In above relation, the torque angle \(\delta_1\) and \(\delta_2\) are associated with winding sets \(a\ b\ c\) and \(a'b'c'\), respectively, and defined as

\[ \delta_1 = \delta_0 \tag{16} \]

\[ \delta_2 = \delta_0 + \theta + \xi \tag{17} \]

\(\delta_0\) is the initial value of load angle, whereas \(\theta\) is the phase difference between voltage fed to phase \(a\) and \(a'\). Hence, torque attributed by each stator winding sets \(a\ b\ c\) and \(a'b'c'\) is given by Equations (12) and (13) may be readily written in \(M-T\) axes,

\[ \tau_{e1} = c(\psi_{M1} I_{T1} - \psi_{T1} I_{M1}) \tag{18} \]
where, the flux linkage $\psi_{Mk}$ and $\psi_{Tk}$, and stator current $I_{Mk}$ and $I_{Tk}$ are aligned along $Mk$–$Tk$ axes respectively, for winding sets $a\ b\ c$ (for $k = 1$) and $a'\ b'\ c'$ (for $k = 2$). Since, the resultant armature air gap flux is only aligned along flux axis (i.e. $Mk$ axis). Therefore, $\psi_{T1} = 0$ and $\psi_{M1} = \psi_{s1}$, where $\psi_{s1} = \sqrt{\psi_{M1}^2 + \psi_{T1}^2}$ (20)

$\psi_{s2} = \sqrt{\psi_{M2}^2 + \psi_{T2}^2}$ (21)

Hence, motor torque equation may be simplified as

$\tau_e = \tau_{e1} + \tau_{e2} = c(\psi_{s1}I_{T1} + \psi_{s2}I_{T2})$ (22)

The developed motor torque is dependent on flux linkage $\psi_{s1}$ (and $\psi_{s2}$) and current $I_{m1}$ (and $I_{m2}$) which are orthogonal. This is the introduction of vector-controlled six-phase synchronous motor. The motor operation during steady state has been shown in the developed phasor diagram in Figure 1.

4. Implementation of vector control scheme

The implementation of developed vector-controlled synchronous motor drive system has been shown in Figure 2. In this paper, motor operation has been investigated in constant torque region up to base speed, but same may be extended in field weakening region above base speed. In the figure, the outer speed loop is used to generate the reference value torque component of stator current $I_{m1}$ through a speed controller (PI controller), whereas the reference value magnetizing current $I_{m1/k}$ is generated by the flux controller (PI controller) associated with each winding sets $a\ b\ c$ (for $k = 1$) and $a'\ b'\ c'$ (for $k = 2$). The reference magnetizing current is used to establish the required flux $\psi_{sm}$ in air gap, which related to field current by the relation,

$$I_{m1} = I_{fr} \cos \delta_1$$
$$I_{m2} = I_{fr} \cos \delta_2$$

In phasor diagram, current component $I_{1s}$ (and $I_{2s}$) is in the direction of $T_1$ (and $T_2$) axis along which the voltage vector is also aligned. Further, the magnetizing component of current $I_{1m}$ (and $I_{2m}$) is
aligned along $M_1$ (and $M_2$) axis which is used to establish the flux vector $\psi_{s1}$ (and $\psi_{s2}$). At steady state, both the stator flux and armature flux vectors are orthogonal to each other, i.e. $\psi_{s1}$ (and $\psi_{s2}$) is perpendicular to $\psi_{a1}$ (and $\psi_{a2}$) as shown in phasor diagram. Therefore, at steady state, both the vectors $I_n$ and $I_s$ are equal i.e. $I_n = I_{s1}$ for winding set $a\ b\ c$ (and $I_{s2} = I_{s3}$ for winding set $a'\ b'\ c'$) and becomes in phase with voltage vector, signifying the motor operation at unity power factor. In control scheme, it may be noted that the magnetizing current component $I_{m1}$ (and $I_{m2}$) is related to field current $I_{frk}$ associated with winding sets $a\ b\ c$ and $a'\ b'\ c'$. Field current commands $I_{fr1}^*$ and $I_{fr2}^*$ are synthesized using Equation (23) in feedback loop. In field control loop, the field current error is fed to the field controller (PI controller) to establish the required field excitation. It may be noted here that the magnitude of field current magnitude associated with each winding set $a\ b\ c$ and $a'\ b'\ c'$ is assumed to be same $I_{frk} = 0.5I_{fr}$. Now, the flux component of stator current is generated by

$$
\begin{align*}
I_{M1}^* &= I_{m1}^* - I_{fr}^* \cos \alpha_1 \\
I_{M2}^* &= I_{m2}^* - I_{fr}^* \cos \alpha_2
\end{align*}
$$

(24)

Above relation will yield a finite value of $I_{M1}^*$ and $I_{M2}^*$. But at steady state, it becomes zero (i.e. $I_{M1}^* = I_{M2}^* = 0$) and Equation (23) will be satisfied. As soon as stator current component $I_{trk}^*$ and $I_{sk)^*}$ are synthesized for winding sets $a\ b\ c$ ($k = 1$) and $a'\ b'\ c'$ ($k = 2$), the reference value of current in stationary reference frame is generated. For this purpose, following two-step transformation is carried out.

1. Current component $I_{trk}^*$ and $I_{sk)^*}$ are transformed to $d-q$ component in stationary reference frame, using angle $\alpha$ in transformation in relation (15).

2. Above obtained stationary $d-q$ component of current is transformed into its equivalent three-phase current (Krause et al., 2004).

The reference current generated in above steps in stationary reference frame are then compared with actual phase current of stator windings which results in current error. This current error is fed to the hysteresis current controller to regulate switching of inverter circuit feeding the motor.
5. Simulation results

The developed system of vector-controlled six-phase synchronous motor drive was implemented in Matlab/Simulink environment. For this purpose, a 3.7-kW motor (parameters are given in Appendix 1) was operated in four quadrant. Initially, speed command was given at time $t = 0.1$ s, in ramp way, following to which motor starts to run at synchronous speed after time $t = 0.65$ s, showing its operation in first quadrant. A load of 50% of base torque was applied at time $t = 1.5$ s which results a small dip in speed by 0.03 rad/s, but regains its original speed (i.e. synchronous speed) after time $t = 0.5$ s, as shown in Figure 3. In order to examine the motor operation in second quadrant, the direction of load torque was reversed at time $t = 3$ s, resulting in a small increase in rotor speed by 0.05 rad/s. A small change in rotor speed due to sudden change in load torque signifies the disturbance rejection property of the drive system. A zoomed view of speed variation has been shown in Figure 3(a). Following to the change in load torque, not only the variation in $q$-component of stator current but also resulted a small variation in $d$-component of current, as shown in Figure 5. Change in stator current is also reflected in $T$-axis component of motor current flowing in winding sets $a b c$ and $a' b' c'$, in Figures 4 and 6. In order to shift the motor operation to third quadrant, a speed reversal command was initiated at time $t = 4$ s in ramp way. The motor is then finally operates in reverse motoring mode after time $t = 5$ s at synchronous speed. Further, at time $t = 6$ s the load torque is reversed to operate the drive in fourth quadrant. It is important to note here that the switching of motor operation to different quadrant results in a large variation in $d$-component stator current whose effect is compensated by rotor field current, as shown in Figure 7(b). But the field circuit has a larger time constant, making the response slow (Das & Chattopadhyay, 1997; Jain & Ranganathan, 2011; Krause et al., 2004). This sluggish response of field circuit is substantially improved due to the magnetizing current injection along flux direction, as depicted by reference value of current in Figure 4(b and c) as well as in actual current in Figure 6(c and d). Input phase voltage fed to winding sets $a b c$ and $a' b' c'$, is shown in Figure 8(a and b), respectively.

6. Conclusion

The scheme of vector control applicable for asymmetrical six-phase synchronous motor has been developed and extensively investigated in four quadrant operation. In this control technique, stator current is maintained for motor operation at unity power factor, which minimizes the stator current...
Figure 4. Reference current in $M$–$T$ coordinate (a) $I_{T1}^*$, (b) $I_{M1}^*$ and (c) $I_{M2}^*$.

Figure 5. Stator current in $d$–$q$ coordinate (a) $i_{q1}$, (b) $i_{d1}$, (c) $i_{q2}$, (d) $i_{d2}$.

Figure 6. Actual current in $M$–$T$ coordinate (a) $I_T$, (b) $I_{T2}$, (c) $I_{M1}$ and (d) $I_{M2}$.
and hence less losses. The dynamic behavior of six-phase synchronous motor in different quadrant operation was found to be substantially improved because of the decoupled/independent control of flux as well as torque component of current along $M$–$T$ axis, respectively. Furthermore, sluggish response of the rotor field circuit was also noted to be improved because of the magnetizing current injection from armature side.

The present work may be further extended and investigated under different practical application with their experimental validation.

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Motor parameter of 3.7 kW, 6 poles, 36 slots are

\[
x = \begin{bmatrix}
x_{1d} + x_{1q} + x_{md} & 0 & (x_{1d} + x_{1q} + x_{md}) \\
0 & x_{1d} + x_{1q} + x_{md} & (x_{1d} + x_{1q} + x_{md}) \\
(x_{1d} + x_{1q} + x_{md}) & -x_{ldq} & (x_{1d} + x_{1q} + x_{md}) \\
x_{ldq} & (x_{1d} + x_{1q} + x_{md}) & 0 \\
(x_{1d} + x_{1q} + x_{md}) & (x_{1d} + x_{1q} + x_{md}) & (x_{1d} + x_{1q} + x_{md}) \\
x_{md} & 0 & (x_{1d} + x_{1q} + x_{md}) \\
0 & x_{mq} & 0 \\
x_{md} & 0 & 0 \\
x_{md} & 0 & 0
\end{bmatrix}
\]

\[
x_{1d} = x_{1q} = 0.1758 \Omega
\]

\[
x_{1d} = 0.210 \Omega \quad x_{1q} = 3.9112 \Omega \quad r_f = 0.056 \Omega
\]

\[
x_{1d} = 0.210 \Omega \quad x_{1q} = 6.1732 \Omega \quad x_{ldq} = 0
\]

\[
x_{1d} = 2.535 \Omega \quad x_{1q} = 0.66097 \Omega \quad x_{md} = 0.001652 \Omega
\]

\[
x_{1d} = 140.0 \Omega \quad x_{ldq} = 1.550 \Omega \quad x_{mq} = 0.2402 \Omega
\]
