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Research Article

Current harmonics elimination control method for six-phase PM synchronous motor drives

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ABSTRACT

To reduce the undesired 5th and 7th stator harmonic current in the six-phase permanent magnet synchronous motor (PMSM), an improved vector control algorithm was proposed based on vector space decomposition (VSD) transformation method, which can control the fundamental and harmonic subspace separately. To improve the traditional VSD technology, a novel synchronous rotating coordinate transformation matrix was presented in this paper, and only using the traditional PI controller in d–q subspace can meet the non-static difference adjustment, the controller parameter design method is given by employing internal model principle. Moreover, the current PI controller parallel with resonant controller is employed in x–y subspace to realize the specific 5th and 7th harmonic component compensation. In addition, a new six-phase SVPWM algorithm based on VSD transformation theory is also proposed. Simulation and experimental results verify the effectiveness of current decoupling vector controller.

1. Introduction

Multiphase motor drives have been recently proposed for applications where some specific advantages can be better exploited, such as lower torque pulsations and dc link current harmonics, higher overall system reliability and better power distribution per phase, etc. [1]. When vector space decomposition (VSD) approach is used to multiphase machines, the variables can be divided into some orthogonal planes, which include one α–β plane and several x–y planes, and the zero-sequence components [2,3], and the vector control method of three-phase motor can also be used. However, due to the existence of additional degrees of freedom, controlling only the torque and flux producing α–β currents is insufficient and additional controllers are necessary to nullify the x–y currents that may flow due to the machine/converter asymmetry and the inverter dead-time effect [4]. Moreover, compare with three-phase machine, some problems of six-phase machines (having two sets of three-phase windings spatially shifted by 30 electrical degrees) are not encountered with conventional three-phase drives, such as large stator current harmonics [5,6], stator current unbalance [4,7], etc. Furthermore, in high power four-quadrant six-phase motor drives, separate dc power supplies that is used commonly to avoid the circulating current is a potential unbalance current sharing when the separated dc links have some difference.

In fact, using VSD transformation method, only per phase current of six-phase PMSM is completely symmetric, $6k\pm1$th, $k=1, 3, 5, \ldots$ harmonics, including 5th and 7th harmonics, can be mapped into x–y plane. There are two main sources for stator current harmonics. The first source is the inverter non-linearity, which can cause large stator current harmonics if the supplied voltage contains harmonic components of the order ($6k\pm1$, $k=1, 3, 5, \ldots$).The second one is the structure of PMSM itself, permanent magnets may produce non-sinusoidal back EMF and rotor saliency, pole shape and possible magnetic saturation can cause harmonics in the air-gap flux [8].

In order to solve with these problems, many control schemes for six-phase machines have been suggested in the literatures. One approach for modeling and control is a double d–q winding representation [9–11]. Although this method can provide excellent performance for current unbalance compensation between two sets, the 5th and 7th current harmonics were only suppressed to some extent due to the limited bandwidth of PI control. Meanwhile, there are mutual coupling voltages between two sets of three-phase windings, which are hard to compensate completely, and hence, its dynamic torque performance may be affected. The other one is the vector control based on VSD method [2–5,12,13]. This method could provide excellent dynamic torque performance without the influence of coupling voltages between two sets comparing with double d–q control method, and the current unbalance can also be compensated by minimizing the currents in x–y plane to be zero, but the current unbalance between phase windings in each set as well as the 5th and 7th current harmonics were not taken into account.

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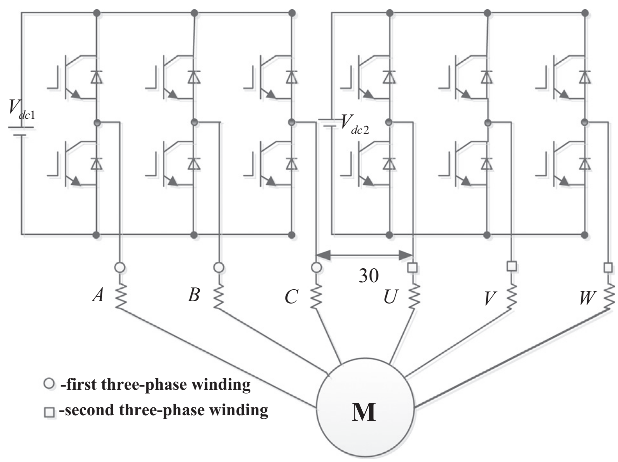

Fig. 1. Six-phase PMSM drive system.

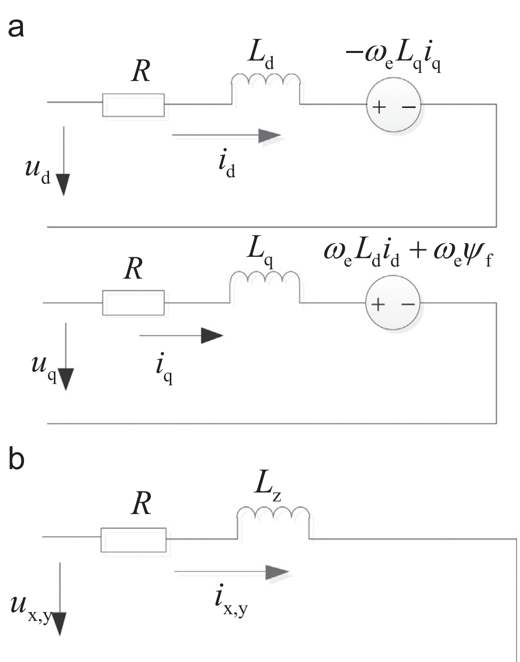

Fig. 2. Voltage equivalent circuit for six-phase PMSM: (a) equivalent circuit in *d–q* plane (b) equivalent circuit in *x–y* plane.

In this paper, a six-phase PMSM and the inverter arrangement are illustrated in Fig. 1, it can be seen that two separate dc powers (supplied by PWM rectifier) are used to supply the two three-phase windings respectively. Compare with multiphase inverter with same dc link, a potential unbalance current sharing will occur easily presented in [14] when the separated dc links have some difference as shown in Fig. 1. In order to solve the above problems, an improved vector control method is presented in this paper, an improved vector control algorithm was proposed based on vector space VSD transformation method. To improve the traditional VSD technology, a novel synchronous rotating coordinate transformation matrix was presented in this paper, and only using the traditional PI controller in *d–q* subspace can meet the non-static difference adjustment, the controller parameter design method is given by employing internal model principle. In addition, the current PI controller parallel with resonant controller is employed in *x–y* subspace to realize the specific 5th and 7th harmonic component compensation. The effectiveness of proposed method is finally verified by a set of comparative simulation and experiment results.

2. Mathematical model of six-phase PMSM

As shown in Fig. 1, the six-phase PMSM presented in this paper has two sets of three-phase stator windings spatially shifted by 30 electrical degrees with isolated neutral points (ABC is the first set of winding, and UVW is another one). Moreover, to ensure each three-phase winding has the same DC voltage, the sets of winding is supplied by the same PWM rectifier respectively.

According to the VSD theory for six-phase motor, through matrix transformation, the machine's six-phase variables can be transformed into stationary reference quantities, which appear in three mutually orthogonal planes, such as α–β plane, x–y plane and zero-sequence plane, and different harmonics are mapped to different planes [3]. The fundamental component and $12k\pm1$th, $k=1, 2, 3\ldots$ harmonics are mapped into α–β plane, while the loss-producing $6k\pm1$th, $k=1, 3, 5,\ldots$ harmonics, including 5th and 7th harmonics, are mapped into x–y plane. Zero-sequence components have been omitted because zero-sequence current cannot flow due to the isolated neutrals. For six-phase PMSM, the following amplitude invariant transformation matrix is employed as:

$$\boldsymbol{T}_{\alpha\beta}=\frac{1}{3}\begin{bmatrix} 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & -\frac{1}{2} & -\frac{1}{2} & 1 \\ 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ -1 & \frac{1}{2} & \frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \end{bmatrix} \tag{1}$$

A rotational transformation is applied next to transform a α–β variables into a synchronously rotating reference, which is suitable for vector control, i.e.,

$$\boldsymbol{T}_{dq}=\begin{matrix} d \\ q \\ x \\ y \end{matrix}\begin{bmatrix} \cos\,\theta_e & \sin\,\theta_e & & \\ -\,\sin\,\theta_e & \cos\,\theta_e & & \\ & & 1 & \\ & & & 1 \end{bmatrix} \tag{2}$$

Assuming that the induced back EMF is sinusoidal, eddy current and hysteresis loss, mutual leakage inductance, and saturation are neglected, two sets of windings are symmetric, the voltage equations of six-phase PMSM in synchronously rotating reference can be expressed as followings:

$$\begin{cases} u_d=Ri_d+L_d\frac{d}{dt}i_d-\omega_eL_qi_q \\ u_q=Ri_q+L_q\frac{d}{dt}i_q+\omega_e\left(L_di_d+\psi_f\right) \end{cases} \tag{3}$$

$$\begin{cases} u_x=Ri_x+L_z\frac{d}{dt}i_x \\ u_y=Ri_y+L_z\frac{d}{dt}i_y \end{cases} \tag{4}$$

where R is the stator resistance, $L_x (x=d, q)$ are the stator inductances, L_z is the leakage inductance, u_x ($x=d, q, x$ and y) is the stator voltage component, i_x ($x=d, q, x$ and y) is the stator current component, ω_e is the electrical angular speed, θ_e is the electrical angular, $\psi_{\rm f}$ is the permanent magnet flux, d/dt is the differential operator.

According to the voltage equations (3) and (4), equivalent circuit can be presented as Fig. 2. It can be seen that the control for six-phase PMSM is decomposed completely. The vector control for six-phase PMSM could be as simple as vector control for single three-phase PMSM.

3. Current harmonics elimination method design

3.1. Principle of current harmonics elimination analysis

Considering the non-sinusoidal back EMF and inverter nonlinearity, 5th, 7th current harmonics in phase currents are inevitable, in order to reduce the current total harmonic distortion and