Research on vector control system of induction motor for electric vehicle

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Abstract: In order to improve the effect of the induction motor controller of the electric vehicle and meet the special requirements of the electric vehicle, an improved method—vector control method is put forward. By analyzing the traditional vector control method, a model of induction motor is established considering stator iron loss and rotor iron loss. This model contains physical model and mathematical model. Mathematical model is set up based on the special requirements of electric vehicles on the induction motor, that is, the induction motor must have a wide speed range and fast torque response. Then, through the extraction of the formula, the dynamic compensation proposal and static compensation proposal can be got. Ultimately, the simulation analysis testifies the effectiveness of the method.

Key words: electric vehicle; induction motor; vector control; iron loss formatting

CLD number: TP346 **Document code**: A
Article ID: 1674-8042(2012)04-0397-08 **doi**: 10.3969/j.issn.1674-8042.2012.04.020

0 Introduction

Electric vehicles use the vehicle power as the power source, requiring that the motor drive system has wide speed range and a fast dynamic response of torque. As a lightweight, efficient and inexpensive motor, induction motor has been widely used in electric vehicles. However, the induction motor control method based on simple model can not meet the requirements of electric vehicles. Now research on induction motor control method for electric vehicle includes the efficiency optimization control based on search method, the efficiency optimization control and minimum stator current control based on the motor loss model, etc[1-4]. These control methods have their own characteristics. Among them, efficiency optimization control method based on the motor loss model can meet the requirements of electric vehicles for the motor speed control system because it has both a wide speed range and a faster dynamic torque response[5]. Relative to the traditional vector control method, the innovation points of this paper are: comparing the simplified model with loss model to build a physical model of induction motor based on the loss model; comparing the traditional vector control method with vector control method based on the loss model to build mathematical model of induction motor based on the loss model; proposing compensation method of induction motor vector control considering iron loss and verify the effectiveness of the compensation scheme.

1 Induction motor vector control

Vector control was first proposed by Dr. Hase K at German Darmstädter Engineering University in 1968, published by Blaschke F with the item "The magnetic field-oriented control" in 1971. The starting point of vector control was to analog DC motor control method to control the AC motor, taking the magnetic field vector direction as the axis benchmark direction and adopting coordinate transformation to realize AC motor speed and flux control decoupling[6].

1.1 Torque formula of DC motor and induction motor and source of vector control methods

According to electromechanics, the principle of motor generating electromagnetic torque can be considered as the result of the interaction of two magnetic fields inside the motor, so motors' electromagnetic torque can be expressed as a unified expression by

$$T_e = \frac{\pi}{2} n_p^2 \Phi_m F_s \sin\theta_s = \frac{\pi}{2} n_p^2 \Phi_m F_r \sin\theta_r, \quad (1)$$

※ **Received data**: 2012-08-22
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where n_p is motor pole number; F_s and F_r are stator and rotor magnetomotive modulus, respectively; Φ_m is main magnetic flux vector modulus of air-gap; θ_s is angle between stator magnetomotive and air-gap synthesis magnetomotive; θ_r is angle between rotor magnetootive and air-gap synthesis magnetomotive.

In DC motor, the axis of main pole is used as direct axis, namely d-axis; Geometry neutral line is used as quadrature axis, namely q-axis. The motor electromagnetic torque equation can be derived from

$$T_e = \frac{n_p}{2\pi}\frac{N_a}{a}\Phi_d I_a = C_{MD}\Phi_d I_a, \quad (2)$$

where

$$C_{MD} = \frac{n_p}{2\pi}\frac{N_a}{a}$$

is factor of DC motor torque.

From Eq. (2), it can be seen that the direction between main pole flux Φ_d and magnetomotive force direction of armature current is always perpendicular to each other and independent of each other. For the excited motor, the main pole flux Φ_d is provided by the excitation current (the stator current) independently. The field current and armature current are two independent circuits, which can be individually controlled to manage the torque.

In induction motor, the stator magnetic potential F_s, the rotor magnetic potential F_r, and synthetic air-gap magnetic potential all rotate with synchronous angular velocity ω_s in space, and the angle between the rotor magnetic potential and air-gap magnetic potential is generally not equal to $\frac{\pi}{2}$. The motor electromagnetic torque equation can be derived by

$$T_e = \frac{\pi}{2} n_p^2 \Phi_m \left(\frac{3\sqrt{2}}{\pi n_p} N_2 I_r\right)\sin\left(\frac{\pi}{2}+\varphi_r\right) = C_{IM}\Phi_m I_r \cos\varphi_r, \quad (3)$$

where

$$C_{IM} = \frac{3\sqrt{2}}{2} n_p N_2,$$

N_2 is the effective number of rotor winding and φ_r is rotor power factor angle.

From Eq. (3), it can be seen that the induction motor electromagnetic torque is the result of the interaction of the air-gap magnetic field and the rotor magnetic potential, but subjects to the constraints of the power factor angle φ_r. Different from DC motor, induction motor air gap flux, rotor current and rotor power factor angle are all the function of slip ratio, which results in the complexity of induction motor torque control.

In summary, the electromagnetic torque relation of the DC motor is simple and easy to control, whereas AC motor electromagnetic relation is complex and difficult to control. But there is a unified torque formula between DC motor and induction motor, so we can transform induction motor torque control to the control mode of DC motor through equivalent transformation. This is the source of vector control method.

1.2 Coordinate transformation principle of vector control method

The final torque control of induction motors can be attributed to the instantaneous control to the stator phase current (i_A, i_B, i_C)[7]. We can produce three-phase fundamental synthesis of magnetomotive force through loading three-phase symmetrical current i_A, i_B, i_C to stator winding. But there is another way to produce a rotating magnetic except three-phase windings. Two-phase stationary winding and two ratating winding can also produce the required rotating magnetic field, as long as the size, speed and steering of the rotating magnetic are the same with the original ratating magnetic field of three-phase stationary windings. It is conclued that the three-phase stationary winding on three-phase static coordinate system is equivalent to the two rotating windings on the two rotating Cartesian coordinate system, and we can know the relationship between three-phase AC symmetrical current i_A, i_B, i_C in the three-phase stationary windings which can be equivalent to a sinusoidal alternating current i_S and i_R in the two stationary windings and sinusoidal alternating current i_S and i_R in the two stationary windings which can be equivalent to a sinusoidal AC current i_α and i_β in the two rotating winding. The corresponding relationship between currents is

$$\begin{cases} \boldsymbol{i}_{SR} = \boldsymbol{A}\boldsymbol{i}_{ABC}, \\ \boldsymbol{i}_{ABC} = \boldsymbol{A}^{-1}\boldsymbol{i}_{SR}, \end{cases} \quad (4)$$

$$\begin{cases} \boldsymbol{i}_{\alpha\beta} = \boldsymbol{B}\boldsymbol{i}_{SR}, \\ \boldsymbol{i}_{SR} = \boldsymbol{B}^{-1}\boldsymbol{i}_{\alpha\beta}, \end{cases} \quad (5)$$

$$\begin{cases} \boldsymbol{i}_{\alpha\beta} = \boldsymbol{C}\boldsymbol{i}_{ABC}, \\ \boldsymbol{i}_{ABC} = \boldsymbol{C}^{-1}\boldsymbol{i}_{\alpha\beta}, \end{cases} \quad (6)$$

where $\boldsymbol{i}_{\alpha\beta} = [i_\alpha, i_\beta]$, $\boldsymbol{i}_{SR} = [i_S, i_R]$, $\boldsymbol{i}_{ABC} = [i_A, i_B, i_C]$ and $\boldsymbol{C} = \boldsymbol{BA}$; $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ is the corresponding transformation matrix.

The idea of induction motor vector control can be deduced by Eqs. (2) - (4) and described as follows.

Define the two-phase rotating magnetic field current components i'_α and i'_β as the control variables, transform them into the current component i'_S and i'_R in the two-phase stationary coordinate system through rotation transformation, then transform them into current control components i'_A, i'_B, i'_C in three-phase static coordinate system through a two-phase/three-phase transformation matrix in order to control the operation of induction motor. From the above, induction motor vector control principle is shown in Fig. 1.

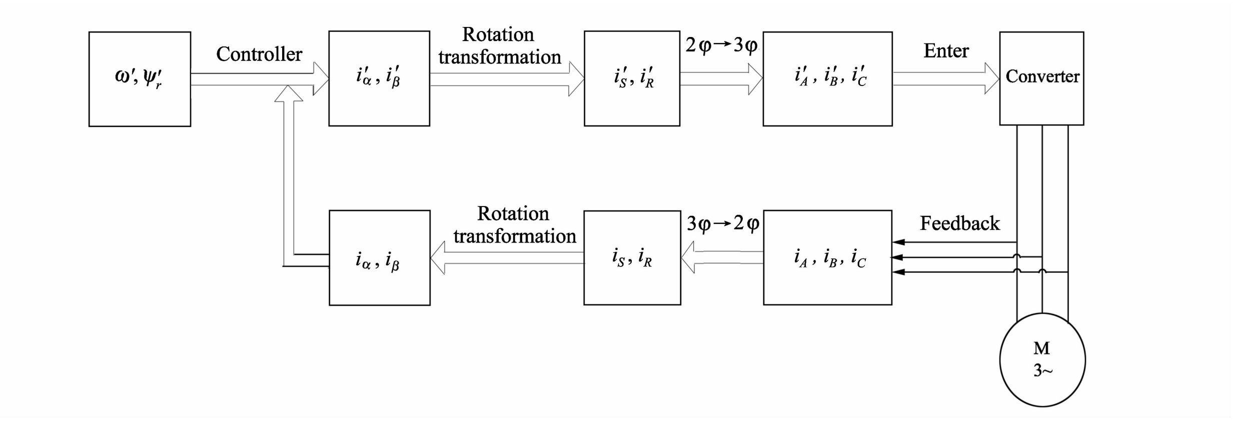

Fig. 1 Induction motor vector control schematic

1.3 Coordinate transformation matrix of vector control method

The transformation matrix that conforms to the induction motor vector control method must meet the following requirements:

1) Transformation matrix should be orthogonal matrix;

2) Transformation matrix should generate the rotating magnetic field before and after the current transformation;

3) Transformation matrix should make motor power the same after voltage and impedance are changed.

Based on Refs. [8]-[10], the transformation matrices are as follows.

Two-phase coordinate system→Three-phase coordinate system($2\varphi\to3\varphi$)

$$\boldsymbol{C}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 0 & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\end{bmatrix}. \tag{7}$$

Three-phase coordinate system→Two-phase coordinate system($3\varphi\to2\varphi$)

$$\boldsymbol{C}^{-1}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 0 & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\end{bmatrix}. \tag{8}$$

Two-phase rotating coordinate system → Two-phase stationary coordinate system($2s\to2r$)

$$\boldsymbol{D}^{-1}=\begin{bmatrix}\cos\theta_r & -\sin\theta_r\\ \sin\theta_r & \cos\theta_r\end{bmatrix}. \tag{9}$$

Two-phase stationary coordinate system → Two-phase rotating coordinate system(2r→2s)

$$\boldsymbol{D}=\begin{bmatrix}\cos\theta_r & \sin\theta_r\\ -\sin\theta_r & \cos\theta_r\end{bmatrix}. \tag{10}$$

where θ_r is the angle between the two coordinate systems of corresponding axis. Rotating coordinate system rotates with angular velocity $\omega_r=\mathrm{d}\theta_r/\mathrm{d}t$.

Three-phase rotating coordinate system → two-phase stationary coordinate system ($3\varphi r\to2s$)

$$\boldsymbol{E}^{-1}=\sqrt{\frac{2}{3}}\begin{bmatrix}\cos\theta_r & \cos(\theta_r-\frac{2\pi}{3}) & \cos(\theta_r+\frac{2\pi}{3})\\ -\sin\theta_r & -\sin(\theta_r-\frac{2\pi}{3}) & -\sin(\theta_r+\frac{2\pi}{3})\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}1 \tag{11}$$

Two-phase stationary cooreinate system → three-phase rotating coordinate system (2s→3φr)

$$\boldsymbol{E}=\sqrt{\frac{2}{3}}\begin{bmatrix}\cos\theta_r & \sin\theta_r & \frac{1}{\sqrt{2}}\\ \cos(\theta_r+\frac{2\pi}{3}) & \sin(\theta_r+\frac{2\pi}{3}) & \frac{1}{\sqrt{2}}\\ \cos(\theta_r-\frac{2\pi}{3}) & \sin(\theta_r-\frac{2\pi}{3}) & \frac{1}{\sqrt{2}}\end{bmatrix}. \tag{12}$$

Using the above-mentioned method, change three-phase stator current of induction motor i_A, i_B, i_C to rectangular axis current i_α, i_β, decoupled excitation component and torque component, then will realize the vector control method of induction motor. However, the drive motor used in electric vehicle has its specific characteristic, which requires the back electromotive force of drive motor with a high speed not to be too high in order to realize a good torque adjusting ability. The back electromotive force of driver is influenced by magnetic inductance L_m, and proportional to L_m, but a too low L_m will influence the torque output capacity of induction motor. In induction motor of an electric car, this contradiction is solved by reducing the number of stator coils and adding the current density of coils. However, this method will produce a lager current and lead to an increasing iron loss of induction motor, especially when the car moving in a high speed. So the traditional method needs to be improved.

2 Vector control method of induction motor with iron loss

Based on the above analysis, iron loss of induction motor in electric vehicle is an important element to influence the efficiency of drive system, as the same as the copper loss. The key point of this paper is to build a model of induction motor with iron loss based on oriented magnetic field of rotor, derivate new formulas for vector control, and put forward static compensation plan compared with the formulas of traditional vector control method.

2.1 Physics model of induction motor with iron loss

Iron loss of induction motor includes stator iron loss and rotor iron loss. We can make it equivalent to the stator and the rotor winding and carry through normalized calculation. Let the number of winding circles equal to the number of stators, and then a physics model of induction motor with iron loss based on traditional induction motor can be built, which is shown in Fig. 2. Relative to the traditional induction motor, there are equivalent winding of iron loss in both stator side and rotor side.

Core loss of induction motor includes magnetic hysteresis loss and eddy-current loss as expressed by

$$p_{\mathrm{Fe}} = p_h + p_e = (k_h f B^2 + K_e \Delta^2 f^2 B^2 V) \approx K_{\mathrm{Fe}} f^{1.3} B^2 G, \qquad (13)$$

where K_{Fe} is loss coefficient of iron core, G is mass of iron core and B is magnetic flux density.

When electric vehicle moving normally, speed of the rotor is close to synchronous speed and the

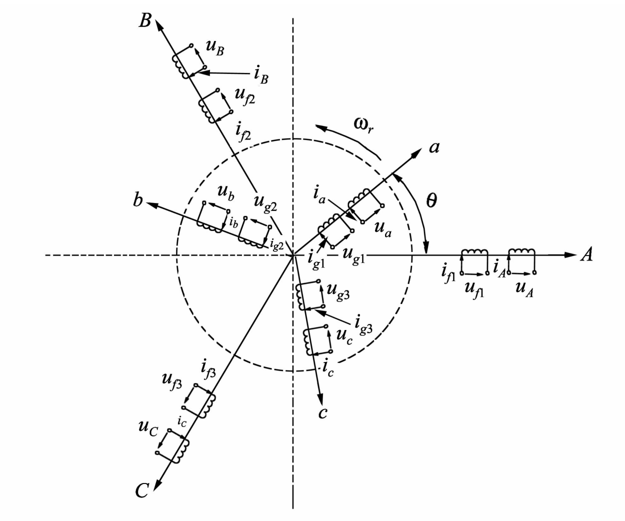

Fig. 2 Model of induction motor with stator & rotor iron loss

alternative frequency of current inside the rotor of induction motor is very low. According to Eq. (13), the iron loss of rotor is very small that it can be neglected and we only consider the iron loss of stators. The physics model is shown in Fig. 3.

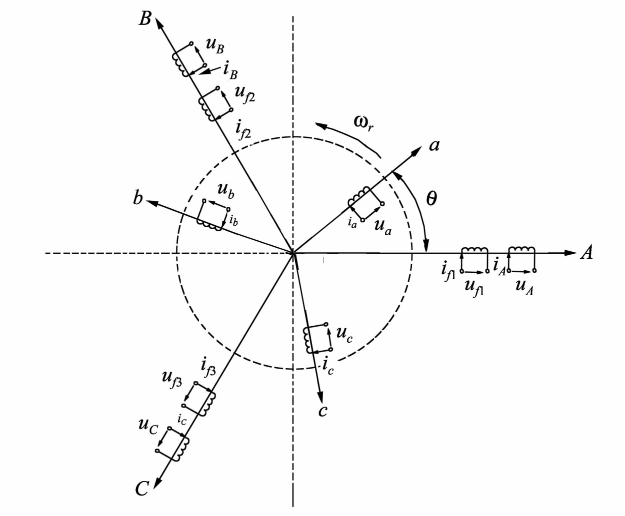

Fig. 3 Physics model if induction motor with stator iron loss only

In Fig. 3, A, B and C denote the three-phase winding axis of the stator, fixed in space, and a, b and c denote the three-phase winding axis of the rotor, turning at an angular velocity of ω_r relatives to the stator, the angle between axis A and axis a is θ, and it changes with the moving of the rotor.

2.2 Mathematical model of induction motor with iron loss and the model after the coordinate transformation

The basic physics model of induction motor is three-phase static and the corresponding mathematical model is three-phase static, too. For the convenience of decoupling of motor flux and torque, it must decouple the excitation components and torque components first. Coordinate transformation of vector control method can realize it. The vector control method of induction motor with iron loss takes the influence of iron loss to the induction motor into account and makes corresponding compensation, furthermore, provides premise and basis for optimization design of controller efficiency subsequently. The model is shown in Fig. 4.

Voltage balance equation of induction motor can write as

$$\boldsymbol{u} = \boldsymbol{Ri} + p\boldsymbol{\Psi}. \tag{14}$$

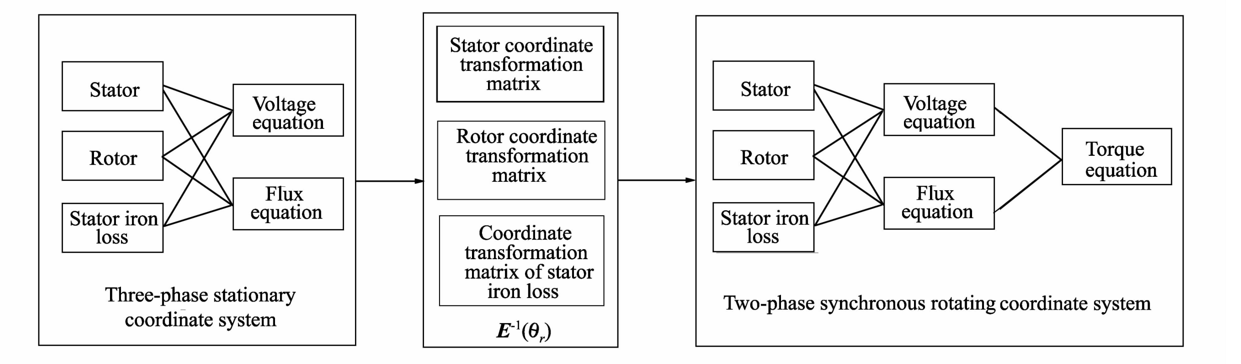

Fig. 4 Mathematical model transformation principle of induction motor

In Eq. (14), voltage vector

$$\boldsymbol{u} = [\boldsymbol{u}_S \quad \boldsymbol{u}_R \quad \boldsymbol{u}_{\mathrm{Fe}}]^{\mathrm{T}},\ \boldsymbol{u}_S = [u_A \quad u_B \quad u_C]^{\mathrm{T}},\ \boldsymbol{u}_R = [u_a \quad u_b \quad u_c]^{\mathrm{T}},\ \boldsymbol{u}_{\mathrm{Fe}} = [u_{\mathrm{Fe}A} \quad u_{\mathrm{Fe}B} \quad u_{\mathrm{Fe}C}]^{\mathrm{T}}.$$

Current vetor

$$\boldsymbol{i} = [\boldsymbol{i}_S \quad \boldsymbol{i}_R \quad \boldsymbol{i}_{\mathrm{Fe}}]^{\mathrm{T}},\ \boldsymbol{i}_S = [i_A \quad i_B \quad i_C]^{\mathrm{T}},\ \boldsymbol{i}_R = [i_a \quad i_b \quad i_c]^{\mathrm{T}},\ \boldsymbol{i}_{\mathrm{Fe}} = [i_{\mathrm{Fe}A} \quad i_{\mathrm{Fe}B} \quad i_{\mathrm{Fe}C}]^{\mathrm{T}},$$

Flux vector

$$\boldsymbol{\Psi} = [\boldsymbol{\Psi}_S \quad \boldsymbol{\Psi}_R \quad \boldsymbol{\Psi}_{\mathrm{Fe}}]^{\mathrm{T}}, \boldsymbol{\Psi}_S = [\Psi_A \quad \Psi_B \quad \Psi_C]^{\mathrm{T}},\ \boldsymbol{\Psi}_R = [\Psi_a \quad \Psi_b \quad \Psi_c]^{\mathrm{T}},\ \boldsymbol{\Psi}_{\mathrm{Fe}} = [\Psi_{\mathrm{Fe}A} \quad \Psi_{\mathrm{Fe}B} \quad \Psi_{\mathrm{Fe}C}]^{\mathrm{T}}.$$

Resistor matrix

$$\boldsymbol{R} = \mathrm{diag}[\boldsymbol{R}_S \quad \boldsymbol{R}_R \quad \boldsymbol{R}_{\mathrm{Fe}}],\ \boldsymbol{R}_S = \mathrm{diag}[R_A \quad R_B \quad R_C],$$
$$\boldsymbol{R}_R = \mathrm{diag}[R_a \quad R_b \quad R_c],\ \boldsymbol{R}_{\mathrm{Fe}} = \mathrm{diag}[R_{\mathrm{Fe}A} \quad R_{\mathrm{Fe}B} \quad R_{\mathrm{Fe}C}].$$

And

$$R_A = R_B = R_C = R_S,\ R_a = R_b = R_c = R_r,\ R_{\mathrm{Fe}A} = R_{\mathrm{Fe}B} = R_{\mathrm{Fe}C} = R_f.$$

Magnetic chain of the windings is the sum of self-induced magnetic chain and mutual induced magnetic chain which comes or is coming from other windings, the flux vector in Fig. 3 can be expressed by the following equation

$$\boldsymbol{\Psi} = \boldsymbol{Li}, \tag{15}$$

where

$$\boldsymbol{L} = \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} & L_{Aa} & L_{Ab} & L_{Ac} & L_{A\mathrm{Fe}A} & L_{A\mathrm{Fe}B} & L_{A\mathrm{Fe}C} \\ L_{BA} & L_{BB} & L_{BC} & L_{Ba} & L_{Bb} & L_{Bc} & L_{B\mathrm{Fe}A} & L_{B\mathrm{Fe}B} & L_{B\mathrm{Fe}C} \\ L_{CA} & L_{CB} & L_{CC} & L_{Ca} & L_{Cb} & L_{Cc} & L_{C\mathrm{Fe}A} & L_{C\mathrm{Fe}B} & L_{C\mathrm{Fe}C} \\ L_{aA} & L_{aB} & L_{aC} & L_{aa} & L_{ab} & L_{ac} & L_{a\mathrm{Fe}A} & L_{a\mathrm{Fe}B} & L_{a\mathrm{Fe}C} \\ L_{bA} & L_{bB} & L_{bC} & L_{ba} & L_{bb} & L_{bc} & L_{b\mathrm{Fe}A} & L_{b\mathrm{Fe}B} & L_{b\mathrm{Fe}C} \\ L_{cA} & L_{cB} & L_{cC} & L_{ca} & L_{cb} & L_{cc} & L_{c\mathrm{Fe}A} & L_{c\mathrm{Fe}B} & L_{c\mathrm{Fe}C} \\ L_{\mathrm{Fe}AA} & L_{\mathrm{Fe}AB} & L_{\mathrm{Fe}AC} & L_{\mathrm{Fe}Aa} & L_{\mathrm{Fe}Ab} & L_{\mathrm{Fe}Ac} & L_{\mathrm{Fe}A\mathrm{Fe}A} & L_{\mathrm{Fe}A\mathrm{Fe}B} & L_{\mathrm{Fe}A\mathrm{Fe}C} \\ L_{\mathrm{Fe}BA} & L_{\mathrm{Fe}BB} & L_{\mathrm{Fe}BC} & L_{\mathrm{Fe}Ba} & L_{\mathrm{Fe}Bb} & L_{\mathrm{Fe}Bc} & L_{\mathrm{Fe}B\mathrm{Fe}A} & L_{\mathrm{Fe}B\mathrm{Fe}B} & L_{\mathrm{Fe}B\mathrm{Fe}C} \\ L_{\mathrm{Fe}CA} & L_{\mathrm{Fe}CB} & L_{\mathrm{Fe}CC} & L_{\mathrm{Fe}Ca} & L_{\mathrm{Fe}Cb} & L_{\mathrm{Fe}Cc} & L_{\mathrm{Fe}C\mathrm{Fe}A} & L_{\mathrm{Fe}C\mathrm{Fe}B} & L_{\mathrm{Fe}C\mathrm{Fe}C} \end{bmatrix}.$$

The above equations form the mathematical model based on three-phase static model of induction motor. Coordinate transformation can change the mathematical model of induction motor from three-phase static axis A, B and C to two phase synchronization axis d and q. The matrix of coordinate transformation is shown in Eq. (11), while (its corresponding electrical angle θ_r is different) corresponding to a different electrical angle θ_r. For stator windings and equivalent windings of iron loss, coordinate system of dq rotates with a synchronous angular velocity ω_r, corresponding θ_r still write as θ_r; for rotor windings, coordinate system rotates with a slip and relative angular velocity ω_c, corresponding θ_r still(then) write as θ_c. So, the conversion matrix from coordinate system with three-phase static to coordinate system with two phase synchronization Eq. (11) can be shown as

$$\boldsymbol{Z} = \begin{bmatrix} \boldsymbol{E}_{\theta_r}^{-1} & 0 & 0 \\ 0 & \boldsymbol{E}_{\theta_C}^{-1} & 0 \\ 0 & 0 & \boldsymbol{E}_{\theta_r}^{-1} \end{bmatrix}. \tag{16}$$

Taking it into Eq. (14), then Eq. (17) is obtained

$$\boldsymbol{Z}\boldsymbol{u}_{dq} = \boldsymbol{R}\boldsymbol{Z}\boldsymbol{i}_{dq} + p\boldsymbol{Z}\boldsymbol{\Psi}_{dp}, \tag{17}$$

where

$$\boldsymbol{u}_{dq} = [u_{ds} \quad u_{qs} \quad u_{0s} \quad u_{dr} \quad u_{qr} \quad u_{0r} \quad u_{d\mathrm{Fe}} \quad u_{q\mathrm{Fe}} \quad u_{0\mathrm{Fe}}]^{\mathrm{T}},$$

$$\boldsymbol{i}_{dq} = [i_{ds} \quad i_{qs} \quad i_{0s} \quad i_{dr} \quad i_{qr} \quad i_{0r} \quad i_{d\mathrm{Fe}} \quad i_{q\mathrm{Fe}} \quad i_{0\mathrm{Fe}}]^{\mathrm{T}},$$

$$\Psi_{dq} = [\Psi_{ds} \quad \Psi_{qs} \quad \Psi_{0s} \quad \Psi_{dr} \quad \Psi_{qr} \quad \Psi_{0r} \quad \Psi_{d\mathrm{Fe}} \quad \Psi_{q\mathrm{Fe}} \quad \Psi_{0\mathrm{Fe}}]^{\mathrm{T}}.$$

Voltage formulas of induction motor after transformation under synchronization reference frame are

$$\begin{cases} u_{ds} = R_s i_{ds} - \omega_t \Psi_{qs} + p\Psi_{ds}, \\ u_{qs} = R_s i_{qs} + \omega_t \Psi_{ds} + p\Psi_{qs}, \\ u_{dr} = R_r i_{dr} - \omega_c \Psi_{qr} + p\Psi_{dr}, \\ u_{qr} = R_r i_{qr} + \omega_t \Psi_{dr} + p\Psi_{qr}, \\ p\Psi_{dm} = R_{\mathrm{Fe}} i_{d\mathrm{Fe}} + \omega_t \Psi_{qm}, \\ p\Psi_{qm} = R_{\mathrm{Fe}} i_{q\mathrm{Fe}} - \omega_t \Psi_{dm}. \end{cases} \tag{18}$$

Flux equations are

$$\begin{cases} \Psi_{ds} = L_{ls} i_{ds} + \Psi_{dm}, \\ \Psi_{qs} = L_{ls} i_{qs} + \Psi_{qm}, \\ \Psi_{dr} = L_{lr} i_{dr} + \Psi_{dm}, \\ \Psi_{qr} = L_{lr} i_{qr} + \Psi_{qm}, \\ \Psi_{dm} = L_m i_{dm}, \\ \Psi_{qm} = L_m i_{qm}. \end{cases} \tag{19}$$

Torque equation is

$$T_e = n_p \frac{L_{\mathrm{m}}}{\mathrm{l}_r} (\Psi_{dr}(i_{qs} - i_{q\mathrm{Fe}}) - \Psi_{qr}(i_{ds} - i_{d\mathrm{Fe}})), \tag{20}$$

where n_p is number of pole pairs; L_m is magnetic inductance; $i_{d\mathrm{Fe}}$ and $i_{q\mathrm{Fe}}$ is equivalent iron loss current of windings of d and q axis, respectively; i_{dm} and i_{qm} is exciting current of d and q axis, respectively; Ψ_{dm} and Ψ_{qm} is main magnetic pole of d and q axis.

2.3 Dynamic and static compensation of vector control method of induction motor with iron loss

In traditional vector control method of induction motor, the direct control variables of magnetic linkage and torque are d and q axis components of stator current, while in vector control method of induction motor with iron loss, axis components of exciting current are used to control magnetic linkage and torque. This method can reduce inaccuracy of traditional method[11], The dynamic and static compensation are also for above reason. (and the above is also the reason for its dynamic and static compensation).

According to rotor magnetic field-oriented vector control method,

$$\Psi_{dr} = \Psi_r, \ \Psi_{qr} = 0. \tag{21}$$

Substituting Eq. (21) into Eqs. (19) and (20), then

$$\begin{cases} i_{ds} = (1 + \dfrac{L_m}{R_{\mathrm{Fe}}} p) i_{dm} - \dfrac{L_m \omega_t}{R_{\mathrm{Fe}}} i_{qm} + \dfrac{p\Psi_r}{R_r}, \\ i_{qs} = (\dfrac{L_r}{L_{lr}} + \dfrac{L_m}{R_{\mathrm{Fe}}} p) i_{qm} + \dfrac{L_m \omega_t}{R_{\mathrm{Fe}}} i_{dm}. \end{cases} \tag{22}$$

Writing it in matrix form

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} 1 + \dfrac{L_m}{R_{\mathrm{Fe}}} p & -\dfrac{L_m \omega_t}{R_{\mathrm{Fe}}} & \dfrac{p}{R_r} \\ \dfrac{L_m \omega_t}{R_{\mathrm{Fe}}} & \dfrac{L_r}{L_{lr}} + \dfrac{L_m}{R_{\mathrm{Fe}}} p & 0 \end{bmatrix} \begin{bmatrix} i_{dm} \\ i_{qm} \\ \Psi_r \end{bmatrix}. \tag{23}$$

Eq.(23) is the dynamic compensation formula of induction motor with iron loss. Removing differential variable p, we can obtain static compensation formula as

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} 1+\frac{L_m}{R_{\mathrm{Fe}}}p & -\frac{L_m\omega_t}{R_{\mathrm{Fe}}} \\ \frac{L_m\omega_t}{R_{\mathrm{Fe}}} & \frac{L_r}{L_{lr}}+\frac{L_m}{R_{\mathrm{Fe}}}p \end{bmatrix} \begin{bmatrix} i_{dm} \\ i_{qm} \end{bmatrix}. \quad (24)$$

3 Simulation and conclusion

Simulate the vector control method of induction motor using Matlab/Simulink. Let $n_p = 2$, $R_s = 0.492\ \Omega$, $R_r = 0.912\ \Omega$, $R_{\mathrm{Fe}} = 500\ \Omega$, $L_m = 0.090$ H, $L_{ls} = 0.008$ H, $L_{lr} = 0.008$ H, $J = 2.1\times10^{-2}$ kg·m^2.

With the purpose of comparison, represent the traditional vector control method, vector control method with dynamic compensation and iron loss, vector control method with static compensation and iron loss by Figs. 5 – 7, respectively. The motor starts up with load of 10 N·m; In Fig. 5 and Fig. 6, the load increases to 15 N·m at 0.3 s. and down to 10 N·m at 0.35 s; In Fig. 7, the load increases to 15 N·m at 1 s, and downs to 10 N·m at 1.05 s (because of the motor is not working with steady state, so the time of changing the load is delayed). when motor starts, setting the maximum of motor torque to be 40 N·m by amplitude limiting effect of torque regulator. In figures, T_e^* denotes given torque; T_e denotes the actual output torque.

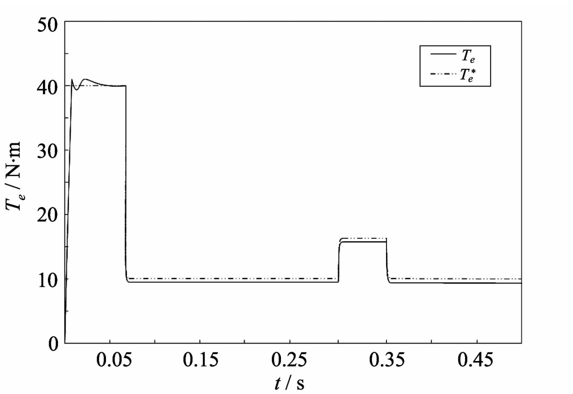

Fig. 5 Traditional vector control method

According to Fig. 5, if employ traditional vector control method, electromagnetic torque will wave in initiating processes, amplitude of the wave will be higher than the maximum of electromagnetic torque. When motor working with steady state and changing load, output electromagnetic torque T_e is less than T_e^*.

According to Fig. 6, if adopt vector control method with dynamic compensation and iron loss, When motor working with steady state and changing load, output electromagnetic torque T_e tracks T_e^* well.

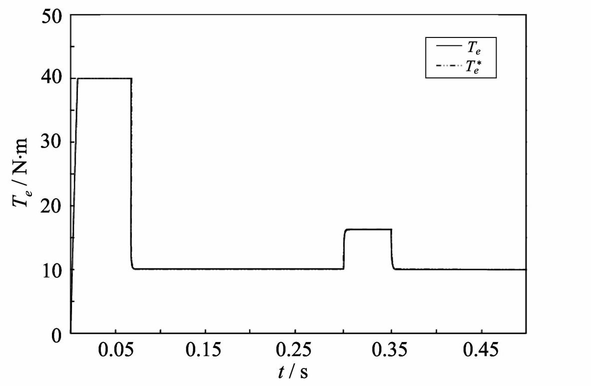

Fig. 6 Vector control method with dynamic compensation and iron loss

According to Fig. 7, if use vector control method with static compensation and iron loss, there is a relative large error in output electromagnetic torque, the torque increases very slowly, and the maximum of electromagnetic torque will much higher than given electromagnetic torque.

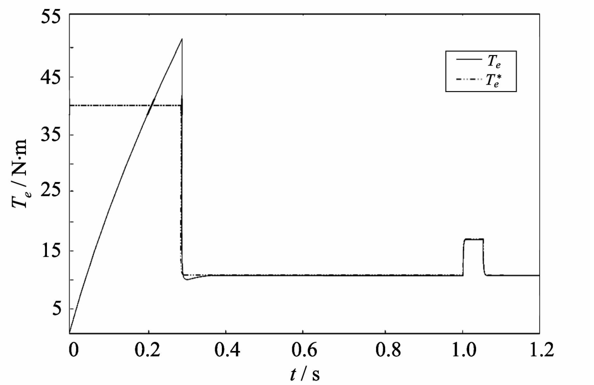

Fig. 7 Vector control method with static compensation and iron loss

In practical application of vector control method with compensation and iron loss, can use the traditional method firstly, and then employ the static compensation method after system working with steady state. In this way, both the motor can start fast and system can track the electromagnetic torque well when operating. Further more, reaction speed of static compensation method is faster than dynamic method, and the static method need more simple hardwares.

This paper expanded the influence of stator and the rotor iron loss to induction motor based on traditional vector control method, and built the physics and mathematical models of induction motor with iron loss. Transferred model of induction motor from three-phase static axis to two phase synchronization reference frame by coordinate transformation, and proceed-ed mathematical calculation, decoupled control of magnetic flux and torque by controlling exciting current of d, q axis in order to control the motor accurately and provide basis for optimized-efficiency of induction motor controller subsequently.

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