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Parameter Estimation of Dual Three Phase PMSM based on the Recursive Least Square Method

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Abstract

During the operation of a dual three-phase PMSM, variations in parameters due to magnetic field saturation and temperature can impact the dynamic response and control accuracy, and the performance of associated algorithms, including those relying on motor parameters for sensorless control. Hence, this paper addresses the challenge of parameter variations in the operation of dual three-phase PMSM by designing an online parameter estimation strategy based on the recursive least square method. The strategy is developed within the framework of the control model for dual three-phase permanent magnet synchronous motor.

Key words: dual three phase PMSM, recursive least square method, parameter estimation

1. Introduction

Dual three phase permanent magnet synchronous motor(DTP PMSM) possess fault-tolerant capability and have found extensive application in electric propulsion system. Typically, to enhance the reliability of motor control system, in addition to installing speed sensor, it is necessary to design additional sensorless algorithm. Moreover, sensorless algorithm that are easy to implement in engineering often rely on the derivation and design based on the mathematical model of the motor[1].

During motor operation, a certain degree of loss occurs, leading to an increase in internal motor temperature. On the other hand, as the speed increases, the internal magnetic field of the motor approaches saturation, causing changes in parameters such as motor resistance, inductance, and flux linkage.

This mismatch between the controller and motor parameters can lead to a decrease in the performance of the motor control system, affecting safe operation[2]. To address this issue, numerous scholars both domestically and internationally have conducted extensive research on the estimation of permanent magnet motor parameters.

The offline parameter estimation method is to complete the parameter calibration before the motor operation, and built into the control program through the look-up table method, but it can not obtain the parameter changes of the motor operation in real time, and the online estimation method includes the least squares method, which is able to realize real-time acquisition of the motor parameters, and at the same time has a high degree of accuracy.

Reference [3] designed a dynamic transformation based forgetting factor recursive least squares method for motor parameter identification. Reference [4] proposed a least squares identification method with a forgetting factor and constructed an identification model based on the voltage transient equation to identify the steady-state and transient inductance values of the motor. Reference [5] studied the multiple parameter identification of permanent magnet synchronous motors using least squares method and proposed a distributed iterative online identification strategy, which has high identification accuracy and improves the problem of simultaneous identification of multiple parameters using least squares method. Reference [6] proposed an online parameter identification strategy for dual three-phase permanent magnet synchronous motors based on improving the least squares method, avoiding the process of calculating the inverse matrix in each iteration. However, this method is based on the VSD model and does not consider changes in parameters to be identified under dual-dq transformation. Reference [7] studied the problem of under-ranking of multi-parameter online identification matrix, and realized the effect of matrix rank increase through the method of injecting current based on the online identification strategy, which realized simultaneous identification of multi-parameters and possessed high identification accuracy.

This paper investigates the general parameter estimation of DTP PMSM, proposing a parameter estimation strategy using different coordinate transformations based on recursive least squares

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method, aiming to improve the performance of vector control and sensorless control algorithms for DTP PMSM. The electric propulsion system studied in this paper consists of a multiphase motor system as shown in the Fig. 1, connected to a DTP PMSM through an on-board DC bus, the dual three-phase permanent magnet synchronous motor, compared to a conventional three phase PMSM, whose similarity is that is driven by a six-phase motor winding through two three-phase inverters, offering higher capacity, increasing control freedom, and improving fault-tolerant control capability.

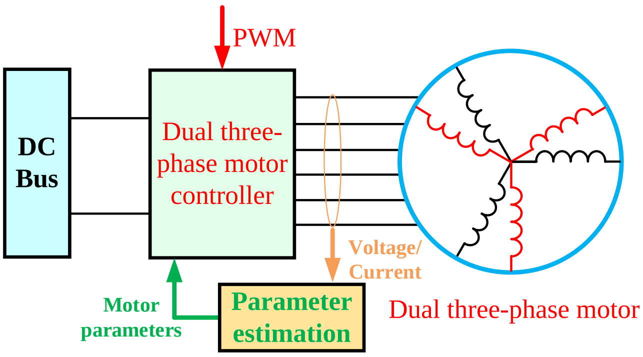

Fig. 1. Dual three-phase electric propulsion system

Based on the aforementioned dual three-phase electric propulsion control system, this study through the research of DTP PMSM coordinate transformation and mathematical model, establish the correct mathematical model basis, combined with the parameter change rule of DTP PMSM during the operation process, based on the recursive least-squares method to derive the DTP PMSM parameter estimation strategy, and analyze the multi-parameter identification approach. Finally, through the establishment of the simulation model, the feasibility of the proposed parameter identification strategy based on the recursive least-squares method to be verified.

2. Mathematical model of DTP PMSM

As previously discussed, the application of DTP-PMSM in electric propulsion systems has great potential. Firstly, this study investigates the vector control of DTP-PMSM. Similar to three-phase motors, in the framework of decoupled transformation of spatial coordinates, the theory rotates the mathematical model of the motor from the natural coordinate system to the orthogonal-axis coordinate system, and finally obtains the equations of the synchronous rotating coordinate system, and the equation of the stator voltage of the dual three-phase motor as shown in equation 2.1.

$$T_{ns/dq} \cdot u_{ns} = T_{ns/dq} \cdot R_n i_{ns} + T_{ns/dq} \cdot \frac{d\psi_{ns}}{dt} \tag{2.1}$$

The $T_{ns/dq}$ denotes the coordinate transformation matrix. According to the coordinate projection relationship can be divided into: 1. based on vector space decomposition(VSD) coordinate transformation, 2. based on dual-dq coordinate transformation[8] as shown in the Fig. 2.

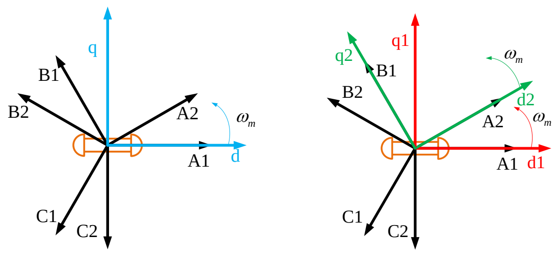

Fig. 2. Synchronous rotation coordinate transformation

The stator voltage equation based on VSD coordinate transformation as shown in equation 2.2, this includes unknown parameters such as d-axis and q-axis inductances and leakage inductances.

$$\begin{bmatrix} u_d \\ u_q \\ u_x \\ u_y \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \\ i_x \\ i_y \end{bmatrix} + \begin{bmatrix} L_D & 0 & 0 & 0 \\ 0 & L_Q & 0 & 0 \\ 0 & 0 & L_{aal} & 0 \\ 0 & 0 & 0 & L_{aal} \end{bmatrix} \frac{\mathrm{d}}{\mathrm{dt}} \begin{bmatrix} i_d \\ i_q \\ i_x \\ i_y \end{bmatrix} + \omega_e \begin{bmatrix} 0 & -L_Q & 0 & 0 \\ L_D & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_x \\ i_y \end{bmatrix} + \omega_e \psi_m \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \tag{2.2}$$

The stator voltage equation based on dual-dq coordinate transformation as shown in equation 2.3, unlike equation 2.2, which includes unknown parameters such as d-axis and q-axis inductances and mutual inductances.

$$\begin{bmatrix} u_{d1} \\ u_{q1} \\ u_{d2} \\ u_{q2} \end{bmatrix} = R_s \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \begin{bmatrix} L_d & 0 & M_d & 0 \\ 0 & L_q & 0 & M_q \\ M_d & 0 & L_d & 0 \\ 0 & M_q & 0 & L_q \end{bmatrix} \frac{\mathrm{d}}{\mathrm{dt}} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \omega_e \begin{bmatrix} 0 & -L_q & 0 & -M_q \\ L_d & 0 & M_d & 0 \\ 0 & -M_q & 0 & -L_q \\ M_d & 0 & L_d & 0 \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \omega_e \psi_m \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} \tag{2.3}$$

In the VSD control method strategy, it is required that the transformation matrix is full rank, due to the existence of DTP PMSM phase shift angle, its different phase shift angle will lead to the transformation matrix can not satisfy the full rank condition. The dual dq control method strategy is more general, the essence is still the DTP PMSM as two three-phase motor decoupling independently, as seen in the above

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equation, for the different coordinate transformation methods, which corresponds to the different decoupling of the state equations in the form, the dual-dq model due to the existence of mutual inductance components, resulting in more complex decoupling of its parameters.

3. DTP PMSM Parameter Estimation strategy

The basic principle of recursive least square method is to seek the best parameter value of the matrix to be estimated by recursiving constantly according to the actual measurement data. The derivation formula of recursive least square as shown in equation 3.1，The algorithm can be realized by adjusting the parameter values of the forgetting factor to have faster convergence speed and stability of the recognition results[2].

$$\begin{cases} P_k = \dfrac{1}{\lambda}\left(P_{k-1} - \dfrac{P_{k-1} x_k x_k^T P_{k-1}}{\lambda + x_k^T P_{k-1} x_k}\right) \\ L_k = \dfrac{P_{k-1} x_k^T}{\lambda + x_k P_{k-1} x_k^T} \\ \widehat{\Theta}_k = \widehat{\Theta}_{k+1} + L_k \left(y - x_k \widehat{\Theta}_{k+1}\right) \end{cases} \tag{3.1}$$

The block diagram of the least squares parameter estimation control strategy as shown in Fig.3.

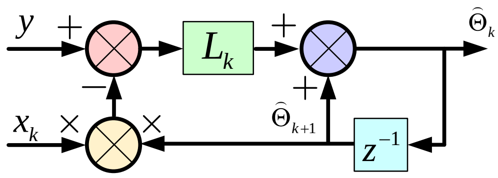

Fig. 3. Control strategy diagram

The essence of the motor parameter estimation matrix construction based on the iterative least squares method is to classify the parameter matrices in the motor state equations according to equation 2.2 and 2.3,. In equation 3.1, $\widehat{\Theta}_k$ is the motor parameter information included in the matrix to be identified, and x and y are used as the input and output parameters respectively, which contain the motor operating voltage and current state information, λ denotes the forgetting factor, P_k represents the state matrix of the operation process .

Compared to resistance parameters, the measurement of motor inductance and magnetic flux parameters is more challenging, and their values are more significantly influenced by motor operation. Considering the accuracy of online parameter estimation, in the subsequent discussions, inductance and magnetic flux will be treated as the objects of parameter estimation. The stator resistance of the motor can be obtained through static measurement.

The recursive matrix of parameters estimation based on VSD coordinate transformation as shown in equation 3.2.

$$\begin{cases} \widehat{\Theta}_k = \begin{bmatrix} \frac{1}{L_d} & \frac{1}{L_d} & \frac{L_q}{L_d} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_q} & \frac{1}{L_q} & \frac{L_d}{L_q} & \frac{\psi_f}{L_q} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{aal}} & \frac{1}{L_{aal}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{aal}} & \frac{1}{L_{aal}} \end{bmatrix} \\ y(k) = \begin{bmatrix} \frac{\mathrm{d}i_d}{\mathrm{d}t} & \frac{\mathrm{d}i_q}{\mathrm{d}t} & \frac{\mathrm{d}i_x}{\mathrm{d}t} & \frac{\mathrm{d}i_y}{\mathrm{d}t} \end{bmatrix}^T \\ x(k) = \big[u_d \;\; -R_s i_d \;\; \omega_e i_q \;\; u_q \;\; -R_s i_q \;\; -\omega_e i_d \\ \qquad -\omega_e \;\; u_x \;\; -R_s i_x \;\; u_y \;\; -R_s i_y \big]^T \end{cases} \tag{3.2}$$

The recursive matrix of parameters estimation based on dual-dq coordinate transformation as shown in equation 3.3.

$$\begin{cases} \widehat{\Theta}_k = \begin{bmatrix} \alpha_1 & \alpha_1 & 0 & 0 & \alpha_1 & \alpha_1 & 0 & 0 & 0 & 0 & \alpha_5 & \alpha_5 & 0 \\ 0 & 0 & \alpha_2 & \alpha_2 & 0 & 0 & \alpha_2 & \alpha_2 & \alpha_6 & \alpha_6 & 0 & 0 & \alpha_9 \\ \alpha_3 & -\alpha_3 & 0 & 0 & \alpha_3 & -\alpha_3 & 0 & 0 & 0 & 0 & \alpha_7 & -\alpha_7 & 0 \\ 0 & 0 & \alpha_4 & -\alpha_4 & 0 & 0 & \alpha_4 & -\alpha_4 & \alpha_8 & -\alpha_8 & 0 & 0 & 0 \end{bmatrix} \\ y(k) = \begin{bmatrix} \frac{\mathrm{d}i_{d1}}{\mathrm{d}t} + \frac{\mathrm{d}i_{d2}}{\mathrm{d}t} & \frac{\mathrm{d}i_{q1}}{\mathrm{d}t} + \frac{\mathrm{d}i_{q2}}{\mathrm{d}t} & \frac{\mathrm{d}i_{d1}}{\mathrm{d}t} - \frac{\mathrm{d}i_{d2}}{\mathrm{d}t} & \frac{\mathrm{d}i_{q1}}{\mathrm{d}t} - \frac{\mathrm{d}i_{q2}}{\mathrm{d}t} \end{bmatrix}^T \\ x(k) = \big[u_{d1} \;\; u_{d2} \;\; u_{q1} \;\; u_{q2} \;\; -R_s i_{d1} \;\; -R_s i_{d2} \;\; -R_s i_{q1} \\ \qquad -R_s i_{q2} \;\; -\omega_e i_{d1} \;\; -\omega_e i_{d2} \;\; \omega_e i_{q1} \;\; \omega_e i_{q2} \;\; -\omega_e \big]^T \end{cases} \tag{3.3}$$

Among，
$$\alpha_1 = \frac{1}{(L_d + M_d)}; \alpha_2 = \frac{1}{(L_q + M_q)}; \alpha_3 = \frac{1}{(L_d - M_d)};$$
$$\alpha_4 = \frac{1}{(L_q - M_q)}; \alpha_5 = \frac{(L_q + M_q)}{(L_d + M_d)}; \alpha_6 = \frac{(L_d + M_d)}{(L_q + M_q)};$$
$$\alpha_7 = \frac{(L_q - M_q)}{(L_d - M_d)}; \alpha_8 = \frac{(L_d - M_d)}{(L_q - M_q)}; \alpha_9 = \frac{2\psi_f}{(L_q + M_q)};$$

include information of motor parameters.

When the DTP PMSM system in operation, taking into account the noise and error in the sampling process, the steady state voltage and current state value of the motor will fluctuate within a certain range, while the average value remains constant, so this paper in the state of the amount of computing using the design of low pass filter to filter out the interference brought about by the high-frequency noise.

According to the above recursive formula, the online parameters estimation of DTP PMSM system under different coordinate transformations can be realized by real time sampling of input and output state variables during the operation of the dual three phase motor control system. The parameter estimation strategy for DTP PMSM system based on the recursive least squares method as shown in Fig. 4.

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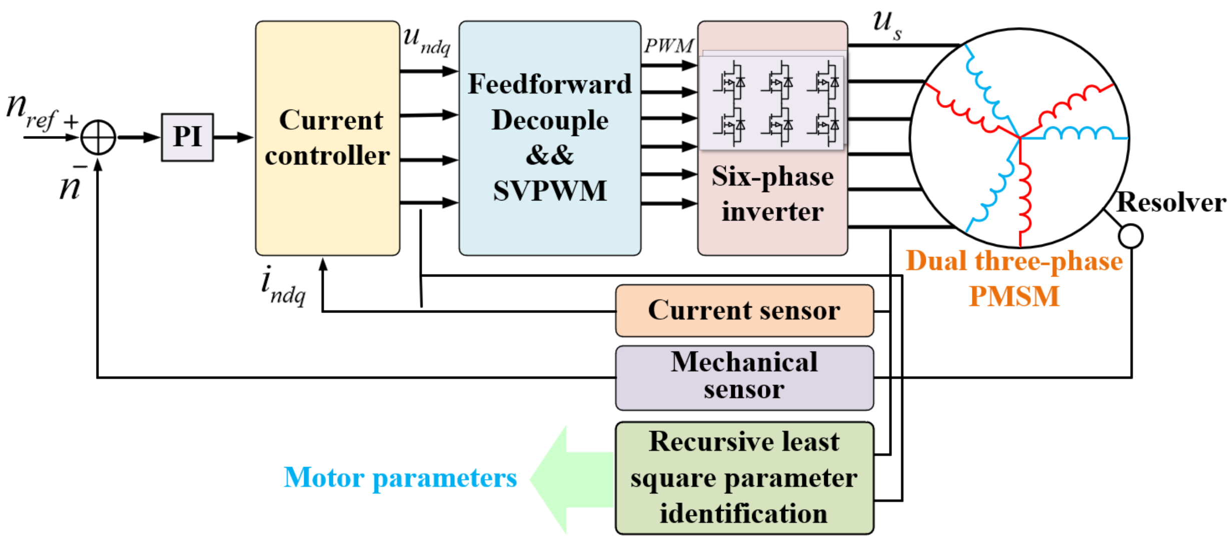

Fig. 4. Block diagram of control system

The parameter estimation matrix obtained from the above derivation is for multi-parameter estimation, but it suffers from the problem of rank deficiency in the estimation matrix. To resolve the matrix convergence issue, one approach is to increase the rank of the estimation matrix by adding input voltage and current state values, such as harmonic current injection. Another method is to employ segmented estimation, reducing the number of parameters to be identified within each estimation calculation cycle to enhance estimation accuracy. Additional voltage compensation is also required in practice, taking into account factors such as dead zones and tube voltage drops.

4. Simulation results

In order to verify the correctness of the proposed DTP PMSM parameter estimation strategy, the control simulation model of the electric propulsion system, which consists of vector control, parameter estimation strategy and DTP PMSM system, is established in SIMULINK. Table 1 lists the parameters of the motors used in the simulation.

Table. 1. Simulation parameters of DTP PMSM

Parameter	Value
d-axis inductance	129.3μH
q-axis inductance	154.3μH
d-axis mutual inductance	100μH
q-axis mutual inductance	120μH
leakage inductance	5μH
Permanent magnet flux	0.0458Wb
Stator resistance	34.68mΩ
Number of pole pairs	20

Establishing the control system model as shown in Fig.5.

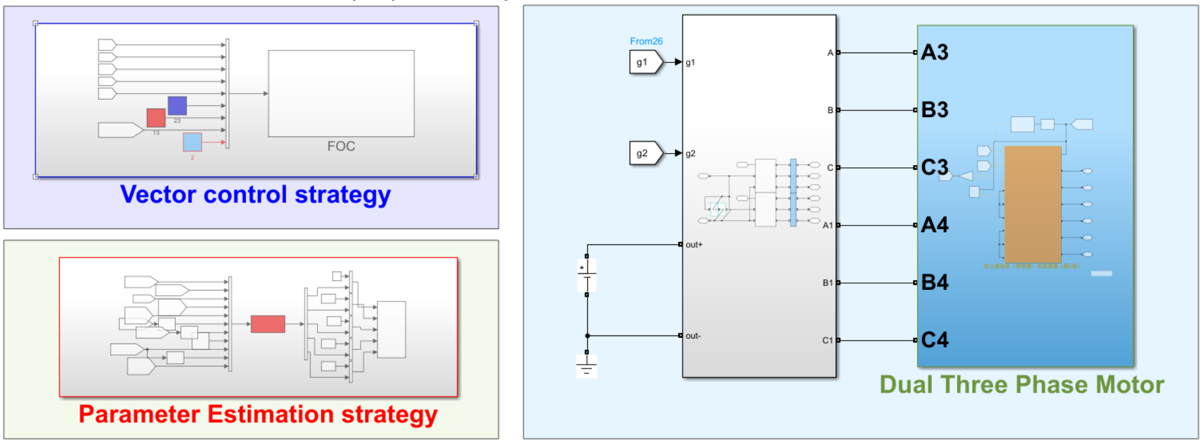

Fig. 5. Simulink simulation control model

The vector control strategies based on VSD coordinate transformation and dual dq coordinate transformation are set respectively, and the parameter estimation strategy based on recursive least squares is simulated under the above control strategies, and the simulation results as shown in Fig. 6.

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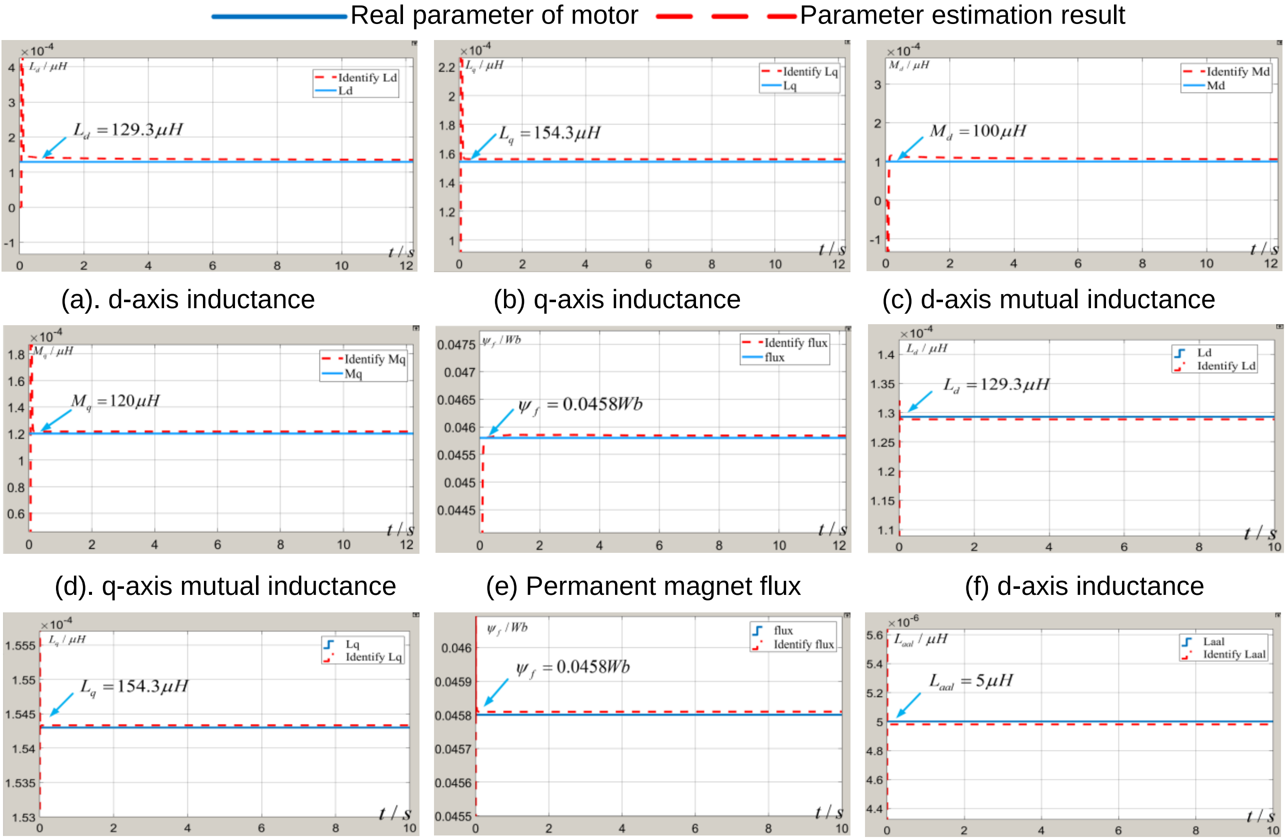

(a). d-axis inductance (b) q-axis inductance (c) d-axis mutual inductance

(d). q-axis mutual inductance (e) Permanent magnet flux (f) d-axis inductance

(g). q-axis inductance (h) Leakage inductance (i) Permanent magnet flux

Fig. 6. Parameter estimation simulation results.(a)-(e) parameter estimation based on dual-dq coordinate transformation. (f)-(i) parameter estimation based on VSD.

According to the simulation results, the proposed parameter estimation strategy is able to realize accurate estimation of real parameters based on both control models and has a fast convergence speed.The feasibility and accuracy of the proposed parameter estimation strategy for DTP PMSM based on the iterative least squares method are demonstrated.

5. Conclusion

This paper mainly proposes a parameter estimation strategy for inductance and magnetic flux linkage based on the least squares method for DTP PMSM control systems. Starting from the mathematical model of DTP PMSM, the influence of parameters on motor control systems is discussed. Two parameter estimation matrices are proposed for DTP PMSM vector space decomposition coordinate transformation and dual-dq coordinate transformation methods. Finally, combined with simulation analysis, the feasibility and accuracy of the proposed parameter estimation strategy are verified under the two control strategies of DTP PMSM.

DTP PMSM have significant advantages in high reliability requirements and large capacity operation, and the research on parameter estimation strategy in this paper can help to provide effective data support for the realization of high performance control, such as sensorless control, which is expected to be widely used in the future electrified transportation electric propulsion system.

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