Research on the Influence of Torque, Speed and Allowable Loss Deviation on the Optimized Current in the Efficiency Optimization Control of IPMSM

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Abstract. In the efficiency optimization control of IPMSM, the working state of the search should be determined by using the search method to obtain the initial optimized current set. For any system, it is expected that the working state of the search should be as little as possible. Meanwhile, according to the initial optimized current set, the interpolation method can be used accurately to realize the efficiency optimization of the whole state. Based on the total loss model of IPMSM, various constraints of running and optimization theory, the equation satisfying the optimization current was obtained, and the influence of motor speed and torque on the optimization current was theoretically analyzed. Through the simulation test of electric drive system of electric vehicle, the optimization current of motor in various states is searched. The simulation results verify the correctness of the theoretical analysis results. Then the number of states to be searched under different allowable loss deviations is analyzed to obtain the initial optimized current set.

Keywords: IPMSM; Efficiency optimization; Torque; Speed; Allowable loss deviation initial; Optimized current.

1. Introduction
With the increasingly serious environmental pollution and the shortage of energy in recent years, countries all over the world begin to pay attention to these two problems and put forward countermeasures. Electric vehicles with the concept of environmental protection and energy saving, by governments around the world to invest heavily, it has become the future development direction of the automobile industry. The embedded permanent magnet synchronous motor (IPMSM) is widely used in the field of electric vehicles due to its advantages of long life, low cost, high power density and high efficiency [1-2].

At present, loss model method and search method are mostly used to optimize the efficiency of electric vehicle drive system. Many scholars have also studied it. Literature [3] and literature [4] adopted the loss model method to optimize the efficiency control of the motor. Since this method is completely based on the mathematical model of the motor, the parameters of the motor have a great influence on it. If the parameters cannot be accurately identified, the application of this efficiency method is invalid. However, the efficiency optimization control based on search technology does not need to list the objective function related to the motor loss. Its preset output power of the motor remains at a specific torque and speed, and this method has good robustness performance for the change of motor parameters [5].

Search method includes online search method and offline search method. In the literature [6], Saurabh Nandy et al. proposed a direct torque control (DTC) search control scheme based on golden section...
method to minimize motor loss. This scheme can directly adjust the stator flux level of the motor and reduce the loss. This algorithm does not need to know the minimum number of function estimation in advance like Fibonacci search method, but it has a large operation. Literature [7] proposes a simple online discrete search algorithm based on gradient-free algorithm, which is more suitable for the highly developed IPM machine tracking MTPA trajectory and has obvious saturation characteristics. In the above mentioned online search method, although it is not necessary to consider the influence of motor parameters on efficiency optimization, the motor should be searched in each control cycle, which takes a long time to search, requires a large amount of computation, and has a slow convergence time. Moreover, it also has high requirements on the controller performance. This method is not applicable to rapidly changing systems. For the off-line search method, Sundareswaran et al. studied an economical and effective off-line method to determine the parameters of the motor equivalent circuit through a load test on the motor [8]. The method transforms the problem of motor parameter identification into a multi-objective optimization problem, and obtains the optimal solution through global search and local search. It avoids the traditional method falling into the local optimum and greatly reduces the optimization time.

In reference [9], a new off-line algorithm is proposed to solve the problem of single-mode search, which uses the pattern search technology and goes through two processes of pretreatment and search. Different parameters are adopted, such as search time, complexity, etc., all of which assume that a fixed number of parameters are taken offline. This method greatly improves the search efficiency and shortens the search time. To sum up, the offline search method only needs to conduct search and calculation in the corresponding software first, and does not need the online DSP to carry out real-time calculation. The real-time calculation amount is very small, and then only needs to look up the table and interpolate. For the system with continuous change of running state, such as the motor, this method is more convenient and fast.

Based on the loss model of the motor, this article analyzes and verifies the influence of motor speed and electromagnetic torque on the optimized current. Based on the influence, the off-line search method is used to divide the corresponding working state interval by loss deviation, so as to obtain the initial optimized current set, make the motor in the process of actual operation, through offline gathering data, do not need to search an infinite number of state, just search the state of the deviation in the allowable range, Finally, the operation of the motor in all states can be realized by initial optimization of current set and interpolation method.

2. IPMSM Efficiency Optimization Modeling

2.1. IPMSM mathematical model

In the coordinate system of synchronous rotation of d/q axis, the equation of state of IPMSM is:

\[
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} = \begin{bmatrix}
    \frac{-R_L i_d + \omega L_q i_q}{L_d} & \frac{\omega L_i}{L_q} \\
    \frac{\omega L_i}{L_d} & \frac{-R_L i_q + \omega L_d i_d}{L_q}
\end{bmatrix} + \begin{bmatrix}
    1/L_d & 0 \\
    0 & 1/L_q
\end{bmatrix} \begin{bmatrix}
    u_d \\
    u_q
\end{bmatrix}
\]

(1)

Where, \( u_d(u_q) \) is the d(q) axial component of stator voltage, \( i_d(i_q) \) is the d(q) axial component of stator current, \( L_d(L_q) \) is the stator inductance component of d(q) axial, \( R_c \) is the stator resistance, \( \omega \) is the angular velocity of electromotive machinery, and \( \varphi_f \) is the flux linkage of the rotor permanent magnet.

The electromagnetic torque expression of the motor is:

\[
T_e = 1.5 P_s \left[ \varphi_f \right. + \left( L_d - L_q \right) i_d] i_q
\]

(2)

2.2. IPMSM loss model

According to the loss analysis of permanent magnet synchronous motor in literature [10], considering the copper loss, iron loss and stray loss, the loss model of IPMSM can be expressed as:

\[
P_l(i_d, i_q) = P_{cu} + P_{fe} + P_{str}
\]

\[
= i_d^T K_1 i_d + K_2 i_d + K_3
\]

(3)
Among them: \( K_1 = (R_s + k_{st})i + k_{fe}A' \), \( K_2 = K_{fe}B' \), \( K_3 = K_{fe}C' \).

### 2.3. IPMSM efficiency optimization model

According to the above loss model, Lagrange optimization theory and IPMSM torque, voltage and current constraints, the efficiency optimization model of IPMSM can be obtained, namely:

\[
\min P(i_d, i_q) = i_d^T K_1 i_d + K_2 i_q + K_3 \\
\text{s.t.} \begin{cases} 
1.5P_{e}\psi_f + (L_q - L_d)i_q \dot{\psi}_q - T_0 = 0 \\
i^T A i + B' i + C' \leq (U_{\text{max}} / \omega)^2 \\
i_d^2 \leq I_{\text{max}}^2
\end{cases}
\]

In equation (4), the graphs of the objective function and various constraints on \( i_d \) and \( i_q \) are shown in Figure I and Figure II respectively.

According to the optimization current solution method in reference [11], the optimization current \( i_q \) meets:

\[
f = n^4 i_d^4 + m^4 i_q - g' = 0
\]

Among them: \( m' = 3(R_s + C_{st}w^2 + C_{fe}w^2 L_d^2)P_{e}\psi_f - 3C_{fe}w^2 \), \( n' = 4.5(R_s + C_{st}w^2 + C_{fe}w^2 L_d^2)P_{e}^2 (L_d - L_q)^2 \), \( g' = 2(R_s + C_{st}w^2 + C_{fe}w^2 L_d^2)T_0 \).
3. Analysis of the Influence of $T_0$ and $\omega_m$ on the Optimized Current

3.1. The Influence of the $\omega_m$

As for the voltage constraint, the higher the speed, the smaller the voltage circle, and the change of motor speed has a certain influence on the optimal current. When the motor parameters: $P_n = 3$, $q = 0.07 \text{Wb}$, $L_d = 375 \mu \text{H}$, $L_q = 835 \mu \text{H}$, $R_s = 29.5 \text{m} \Omega$, $C_p = 2.1 \times 10^{-2}$, $C_m = 6.5 \times 10^{-9}$, $U_{DC} = 240 \text{ V}$, $J = 0.075 \text{ kg} \cdot \text{m}^2$, If the electromagnetic torque of the motor is constant, the influence of the motor speed on the optimized current can be analyzed from equation (5), as shown in Figure III. The change of optimization current $i_q$ and $i_d$ with motor speed $\omega_m$ is shown in Figure III (a) and (b).

![Figure 3] (A) Influence of rotational speed $\omega_m$ on optimized current $i_q$

![Figure 3] (B) Influence of rotational speed $\omega_m$ on optimized current $i_d$

Figure 3. Influence of rotational motor speed on optimized current.

From Figure III (a) and (b), it can be more obviously observed that the value of the optimized current changes very little and hardly changes when the rotation speed changes. Especially when the speed is large, the speed changes and the optimization current remains basically constant.

3.2. The Influence of the $T_0$

According to formula (5), when the torque changes, the optimization current $i_q$ will change. According to the electromagnetic torque equation, namely equation (2), the optimization current $i_d$ will change accordingly. Therefore, the change of torque has an impact on the optimization current. According to equation (5), the influence of the electromagnetic torque of the motor on the optimized current is analyzed. When the motor speed is constant, the result is shown in Figure IV below.

![Figure 4] (A) Influence of torque $T_0$ on optimization current $i_q$
According to Figure IV (a) and (b), when the torque $T_0$ increases, the values of the optimized current $i_d$ and $i_q$ will change greatly.

4. Simulation Test Verification and Analysis

Based on the above theoretical analysis, it can be seen that the loss model-based loss minimization control of IPMSM drive system is essentially: solve the optimization problem of equation (5) to obtain the optimal $i_d$ and $i_q$, and realize the closed-loop control of the motor with the current. Based on matlab simulation software and formula (5), the efficiency optimization control system of IPMSM was established, and the golden section search algorithm was adopted to search the optimized current under different states, namely, different torque and rotation speed, and the influence of motor speed and electromagnetic torque on the optimized current was obtained by test. The simulation system is shown in Figure V below. By running the simulation system, the optimized current under different states (different torque and speed) was searched, and the simulation results as shown in Figure VI below were obtained.

(A) Influence of torque on optimization current($\omega_m$ remains constant)
As can be seen from Figure VI (a) and (b), when the motor speed is constant and the electromagnetic torque changes, the optimization current $i_d$ and $i_q$ will also change accordingly. When the motor torque remains unchanged and the speed changes, $i_d$ and $i_q$ are a straight line, that is, the value does not change. Just because the electromagnetic torque has an effect on the optimization current, while the motor speed has almost no effect on it, in Figure VI (c), the three-dimensional surface of $i_d$ about $T_0$ and $\omega_m$ generates a series of contour lines, which are parallel to the rotation speed axis. The test verifies the correctness of the above theoretical analysis.

5. Analysis of the Influence of Allowable Loss Deviation on the Optimized Current

In practice, when the motor efficiency optimization based on offline search is implemented, some working states of the motor are generally searched offline, and then the full-state efficiency optimization of the motor is realized based on interpolation method. Based on the above analysis, since the motor speed and torque have different influences on the optimal current of the motor, the state that needs to be searched offline cannot be based on the torque and speed interval of the whole operation range of bisect IPMSM. Therefore, the interval should be divided according to the influence degree of torque and speed on the optimal current, that is, the extent influence of motor loss. According to the motor speed and torque diagram of electric vehicle in city or suburb similar to Figure VII below, the torque and speed range of electric vehicle electric drive system is determined. For each working area, select a working point in the interval. In the actual operation process, if the efficiency optimization control is carried out, the difference value of motor loss corresponding to any two operating state points on the boundary of the interval shall not exceed a certain set value. In the offline search, only the selected running state point in each interval is searched, and the optimized current obtained by the search forms the initial optimized current in the interval. Of course, we expect that the less running state of the motor is searched offline, the better, and the smaller the deviation between the actual loss and the optimal loss is when the interpolation realizes the efficiency optimal control of the motor, the better.
Obviously, the two are contradictory, which needs to be compromised. When the allowable loss deviation is relatively small, the operating state of the search should be more, and the working interval is relatively narrow. When the allowable loss deviation is large, the operating state of offline search is less and the working interval is wider.

**Figure 7.** Torque and speed of HEV permanent magnet synchronous motor (on urban roads).

If the motor has the parameters shown in section A in II, and the range of motor torque and speed is as shown in Figure VII, if the allowable motor loss deviation is 5W and 30W, the working area diagram as shown in Figure VIII below can be obtained. The relationship between loss deviation and the number of working states is shown in Table I.

| Tc/Nm | 0 | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
|-------|---|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| n0    | x | x  | x   | x   | x   | x   | x   | x   | x   | x   | x   |
| n1    | x | x  | x   |     |     |     |     |     |     |     |     |
| n2    | x | x  |     |     |     |     |     |     |     |     |     |

(A1) Work area diagram with loss deviation of 5W

(A2) RED local enlargement diagram with loss deviation of 5W
According to Figure VIII (a), (b) and Table I, the larger the loss deviation is, the smaller the number of operating states that need to be searched offline is, that is, the smaller the working interval is. Where, the red rectangular box represents the local enlarged image. For example, When the deviation is 5W, the number of states is 2615, that is, the workspace (center points) has 2615. Thus, When the deviation is 5W, we need to calculate the optimized current at each point in the range of torque 0 to 200N·m and speed 100 to 3000 r/min. The current at these 2615 center points needs to be calculated. In other words, during the actual operation of the motor, the 2615 states need to be searched offline to obtain the initial optimized current set. Based on this, the efficiency optimization of the motor in various states can be realized through the interpolation method of online search. When the deviation is 30W, just search 813 states offline to get the initial optimized current set, and the other deviations are the same as the above principle.
6. Conclusion
In this paper, the influence of motor speed and electromagnetic torque on the current of d and q axis is obtained from both theoretical and experimental two aspects, that is, the motor speed has basically no influence on the current of d and q axis, while the electromagnetic torque has a great influence on them. Therefore, the working state of the system is determined by offline search. When the allowable loss deviation is different and the number of operating states is different, different operating intervals are divided, so that different initial optimized current sets can be obtained. So it can be seen from the analysis in this paper that when the motor is in the process of efficiency optimization control in actual operation, according to the principle of compromise treatment, First, according to the above off-line search method, the working state within the allowable deviation range is searched to obtain the initial optimized current set. Then, the efficiency optimization of the whole state can be realized through interpolation method, greatly save the time.

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