Efficiency Optimization Control of Direct Drive Permanent Magnet Synchronous Motor

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Abstract

High-performance permanent magnet synchronous motor (PMSM) systems used in electric vehicle (EV) are required to deliver high efficiency over the wide speed and torque ranges. This paper proposes a novel efficiency optimization control strategy of PMSM system EV which can maximize the system efficiency in both steady and dynamic state. As the PMSM is directly connected with the load, caused the output torque of motor is a function of the rotate speed, this study is focused on the dynamic system model with the driving cycle which considers about motor copper loss, motor iron loss and inverter loss. Based on the dynamic system model, the proposed control strategy can optimize motor loss and inverter loss together, by which the system efficiency is increased over the whole operation duty. Compared with traditional control strategy, the proposed control strategy can decrease the energy consumption over the whole driving cycle. Both theoretical analysis and experimental results verifies the validity of proposed efficiency optimization control strategy.

Keywords: efficiency optimization control, motor loss, inverter loss, drive cycle, PMSM system

1. Introduction

As a limited energy system, the energy consumption in the driving cycles will directly affect the endurance and loads of EVs. To improve the performance of EVs, it is important to increase the efficiency of power and energy management system. The PMSM system provides driving force for EVs and lead a large part of loss in the power and energy management system. Therefore, to decrease the energy consumption, it is significant to enhance the system efficiency of PMSM system.

There are several control strategies for PMSM system, such as id=0 control [1], MTPA control [2], unity power control [3] and loss model control [4], etc. The id=0 control, MTPA control and unity power control only focus on parts of system loss which will not obtain the maximum efficiency of PMSM. The loss model control can achieve the minimum motor loss by optimizing both copper loss and iron loss in the steady state. There are also a few modulation control strategies for power converters, such as space vector PWM, selected harmonic elimination PWM and minimum switching loss PWM, etc. All these control strategies only consider about parts of system loss and ignore the coupling relationship between PMSM and inverter.

This paper proposes a nonlinear system loss model of PMSM direct drive system which consists of both motor loss and inverter loss. As the PMSM is drove by the three-phase half-bridge inverter, there must be harmonic current in winding caused by the PWM output voltage, which will generate harmonic loss in the PMSM. This paper applies double Fourier integral analysis theory to calculate the fundamental components and harmonics of stator current, by which a whole-frequency loss model of PMSM is created to consider about fundamental motor loss and harmonic motor loss together. To obtain an accurate inverter loss with sinusoidal current in PMSM, the polynomials are used to fit the nonlinear conduction and switch characteristics of power devices. Based on the nonlinear system loss model of PMSM direct drive system, a novel control strategy named efficiency optimization control is proposed in this paper which can optimize motor loss and inverter loss together. The efficiency optimization control can increase the system efficiency in both stead-state and dynamic-state, and significantly improve the energy consumption. The proposed control strategy is verified by both theoretical analysis and experimental results.

2. System loss model of PMSM direct drive system

Figure 1 shows the typical topology of PMSM direct drive system.
2.1 Fundamental loss of PMSM

The fundamental model of PMSM decoupled into d-axis and q-axis is shown in Figure 2.

![Figure 2](image)

**Figure 2** Decoupled mathematic model of PMSM: (a) Dynamic mathematical model in d-axis; (b) Dynamic mathematical model in q-axis.

From Figure 2, the fundamental voltage equation of PMSM in the dynamic-state can be shown as

\[
\begin{align*}
    u_d &= L_{ld} \frac{di_d}{dt} + R_i i_d + L_{md} \frac{di_d}{dt} - n_p \omega_L L_q i_q \\
    u_q &= L_{lq} \frac{di_q}{dt} + R_i i_q + L_{mq} \frac{di_q}{dt} + n_p \omega_L L_q i_d + n_p \omega \psi_f
\end{align*}
\]

(1)

Based on the equation (1), the fundamental copper loss can be expressed as

\[
P_{Cu,f} = \frac{3}{2} R_i \left( i_d^2 + i_q^2 \right)
\]

(2)

This paper applies the Bertotti iron loss formula [5] to evaluate the iron loss, by which the iron loss per volume can be shown as

\[
dP_{fc} = k_b B_n^2 f + \frac{\pi^2 \sigma k_1^3}{6} B_n^2 f^2 + k_b B_n^{1.5} f^{1.5}
\]

(3)

Based on the Bertotti iron loss formula, the fundamental iron loss can be expressed as

\[
P_{fc,f} = dP_{fc,d} V_d + dP_{fc,q} V_q
\]

\[
= \frac{3}{2} k_{bd} \left( (L_d i_d + \psi_f)^2 + (L_q i_q)^2 \right)
\]

(4)

\[
+ \frac{3}{2} k_{bp} \left( (L_d i_d + \psi_f)^{1.5} + (L_q i_q)^{1.5} \right)
\]

Therefore, from equation (2) and equation (4), the fundamental loss of PMSM can be shown as

\[
P_{motor,f} = P_{fc,f} + P_{j,Cu} = \frac{3}{2} R_i \left( i_d^2 + i_q^2 \right)
\]

\[
+ \frac{3}{2} k_{bd} \left[ \left( L_d i_d + \psi_f \right)^2 + \left( L_q i_q \right)^2 \right]
\]

\[
+ \frac{3}{2} k_{bp} \left[ \left( L_d i_d + \psi_f \right)^{1.5} + \left( L_q i_q \right)^{1.5} \right]
\]

(5)

2.2 Harmonic loss of PMSM

To optimize the harmonic motor loss, it is useful to calculate the harmonic components of stator current by an analytic method. This paper applies double Fourier integral analysis to exactly identify the harmonic components of PWM output voltage in the inverter, which ensures the correct harmonics are accurate.

In double Fourier integral analysis theory [6], the PWM output voltage of inverter can be obtained by two time variables \(x(t)\) and \(y(t)\),

\[
\begin{align*}
    x(t) &= \omega_d t + \theta_d \\
    y(t) &= \omega_q t + \theta_q
\end{align*}
\]

(6)

Therefore, the PWM voltage can be presented as

\[
a_n(t) = f(x(t), y(t)) = \begin{cases} 
    U_{dc} & \text{if } y(t) > x(t) \\
    0 & \text{if } y(t) \leq x(t)
\end{cases}
\]

(7)

The time-varying function \(f(x(t), y(t))\) can be expressed as a summation of harmonic components, which are shown as

\[
a_n(t) = \sum_{n=1}^{\infty} \sum_{(m,n) \neq (0,0)} A_{mn} \cos[m(\omega_d t + \theta_d) + n(\omega_q t + \theta_q)] + B_{mn} \sin[m(\omega_d t + \theta_d) + n(\omega_q t + \theta_q)]
\]

(8)

And the fundamental and harmonic coefficients can be expressed as

\[
\begin{align*}
    A_n &= \frac{\sqrt{2} U_{dc}}{\pi n} \\
    B_n &= \frac{\sqrt{2} U_{dc}}{\pi n}
\end{align*}
\]

(9)

where \(M\) can be shown as
The amplitude of harmonic current can be expressed as

\[ M = \sqrt{3(u_d^2 + u_q^2)} \]  

(10)

The equation (9) and (10) shows that the harmonic coefficients is affected by the terminal voltage of PMSM. Based on the motor model of PMSM, the amplitude of harmonic current can be expressed as

\[ I_{s1} = \frac{\bar{u}_{s1}}{R_s + j\omega_m L_s} \]  

(11)

Similar to the calculation of fundamental loss, the harmonic copper loss and harmonic iron loss can be shown as

\[
P_{loss, h} = 3 \left[ \sum_{n=2}^{\infty} R_{s, h} I_{s1}^2 + \sum_{m=1}^{\infty} \sum_{n=0}^{\infty} R_{m, h} I_{s1}^2 \right]  
+ \left( \sum_{n=2}^{\infty} k_{d, h} (L_s I_{s1})^2 + k_{q, h} (L_s I_{s1})^{1.5} \right) \]  

(12)

2.3 Nonlinear loss model of inverter

To acquire accurate inverter loss in the PMSM drive system, it is important to create exact model of power devices. The Figure 3 shows that traditional linear model can only obtain accurate loss at rated working point, and will cause great computational error when the current is away from rated point. As the PMSM direct drive system has the sinusoidal current which is changing all the time, the traditional linear model will not obtain enough accurate inverter loss. Therefore, this paper use polynomials to fit the nonlinear conduction and switch character.

![Figure 3 Conduction characteristics of power devices](image)

The nonlinear conduction characteristics can be fitted as

\[ u_{s1} = a_s + b_s I_{s1} + c_s I_{s1}^2 \]  

(13)

As shown in Figure 3, the nonlinear model can almost accurately fit the nonlinear conduction characteristic of power device in the whole operation range of PMSM direct drive system.

The average conduction losses of the power device in a current period can then be expressed as

\[
P_{loss, conduction} = \frac{1}{T_{current}} \int_0^{T_{current}} d_{ave} \cdot u_{s1} \cdot i_{s1} \, dt \]  

(14)

Similar to conduction characteristics, the nonlinear switch characteristics can also be fitted as

\[
E_{on} = \frac{U_{dc}}{U_{dc, test}} \left( a_{on} + b_{on} \cdot i_{s1} + c_{on} \cdot i_{s1}^2 \right) 
\]

\[
E_{off} = \frac{U_{dc}}{U_{dc, test}} \left( a_{off} + b_{off} \cdot i_{s1} + c_{off} \cdot i_{s1}^2 \right) \]  

(15)

The switching loss in a current period can be expressed as

\[
P_{loss, switch} = \frac{1}{T_{current}} \int_0^{T_{current}} \left( E_{on} + E_{off} \right) \, dt \]  

(16)

Based on equation (14) and (16), the inverter loss of PMSM drive system can be derived as

\[
P_{loss, inverter} = \frac{I_s}{8\pi} \left[ -6(b_s - b_f) I_s M - 9/8(c_s - c_f) I_s^2 M \cos(3\phi) \right]  
+ 16\sqrt{3}(b_s - b_f) I_s M \cos\phi + 4\sqrt{3}(a_s - a_f) M \cos\phi \]  

(17)

2.4 Loss model of PMSM system

From equation (5), (12) and (17), the system loss can be described as

\[
P_{loss, system} = P_{water-f} + P_{water-g} + P_{loss, inverter} \]  

\[
= \frac{3}{2} R_s (i_d^2 + i_q^2) + \frac{3}{2} k_{d, w} \left[ (L_s i_d + \psi_f)^2 + (L_s i_q)^2 \right]  
+ \frac{3}{2} k_{q, w} \left[ (L_s i_d + \psi_f)^2 + (L_s i_q)^2 \right]  
+ \sum_{n=2}^{\infty} \sum_{m=0}^{\infty} R_{m, w} I_{s1}^2 \]  

+ \sum_{n=2}^{\infty} \sum_{m=0}^{\infty} k_{m, w} (L_s I_{s1})^2 + k_{q, w} (L_s I_{s1})^{1.5} \]  

(18)

Substituting equation (1) and (10), the system loss can be simplified as

\[
P_{loss, system} = f(i_d, i_q, \omega_f, f_wm) \]  

(19)

3. Efficiency optimization control of PMSM direct drive system

From equation (19), the system loss of PMSM direct drive system is a function of d-axis current, q-axis current, motor speed and PWM frequency. As the q-
axis current can be described by electromagnetic torque as

\[ i_q = \frac{2T_f}{3\psi_f + (L_{qy} - L_{qy})i_d} \] (20)

Therefore, substituting equation (20) to (19), the system loss can be delivered as

\[ P_{loss,system} = f(i_d, T_f, \omega_f, f_{sw}) \] (21)

The equation (21) shows that the system loss of PMSM drive system is a function of d-axis current, electromagnetic torque, motor speed and PWM frequency. And for a constant working point, the system loss is only a function of d-axis current and PWM frequency. Therefore, there must be optimum d-axis current and PWM frequency for each constant operation condition, which can achieve the lowest loss of PMSM drive system.

Based on the system loss model, this paper proposes the efficiency optimization control to keep the d-axis current and PWM frequency at optimal value over the whole operation range, by which the motor loss and inverter loss are optimized together.

The equation (18) shows that the system loss is too complicated to be solved by analytic method. Therefore, this paper applies GA to obtain the optimized d-axis current and PWM frequency in the both steady-state and dynamic state. The PWM frequency affects the THD of current, which will impact on the system stability. To maintain the system stable, the current THD should below the maximum value. Therefore, the optimum value can be solved by GA as

\[
\begin{align*}
\text{Min} \left( P_{loss,system} \right) &= \text{Min} \left[ f(i_d, i_d, \omega_f, f_{sw}) \right] \\
&\leq \text{THD}_{\text{max}} \quad (22)
\end{align*}
\]

4. Experiments

In order to verify the effectiveness of the proposed control strategy with respect to conventional control, the experimental platform of is designed and implemented as shown in Figure 5.

Figure 5 PMSM test platform

Figure 6 shows the difference of system efficiency between traditional control strategy and proposed control method. Compared with traditional control method, the proposed control strategy can increase the system efficiency over the whole operation range of PMSM direct drive system and will obviously improve the mileage of EVs among the driving cycle.

5. Conclusion

Based on the system loss model, an efficiency optimization control strategy is proposed to optimize motor loss and inverter loss together in the both steady-stage and dynamic-stage. The efficiency optimization control can significantly decrease the energy consumption of PMSM system.

Reference