Analysis and Improvement of High Efficiency and Low Cost Drive System based on Direct Torque Control

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Keywords

Abstract
In this paper, an optimal reference stator flux strategy is proposed to improve the drive system efficiency under direct torque control (DTC). A novel low cost interior permanent magnet synchronous machine (IPMSM) is introduced and used. Based on the easily implementable loss model (LM), the controllable electrical losses which consist of copper loss and iron loss have been minimized under optimal stator flux. Based on finite element method (FEM), the harmonics which is produced by inverter is injected into FEM model; the nonlinear machine parameters and its influence to LMC are also considered. The drive performance’s effectiveness of the proposed scheme is validated in experiment.

Introduction
Based on the limited capacity of battery, the efficiency optimization of electric motor drive system becomes much more necessary than conventional internal combustion engines (ICEs). Since 1983, the concept of minimum input and maximum efficiency operation have been introduced [1]. Until now, significant efforts and attention are given to improve the system efficiency and reducing the equipment cost. The optimization of IPMSM machine and inverter design has received considerable attention [2-4]. Regarding the efficiency optimization strategies, there are mainly two kinds of strategies for electric drive system: loss model control (LMC) and online search control (SC) [5].

The principle of LMC is that an accurate machine model is built; it includes the machine loss over the full operating speed range. Based on the speed and current signals, the minimum loss by using optimal armature current or optimal flux linkage can be found. Due to the existence of stator winding resistance, copper loss becomes one part of the machine loss. In reference [1], maximum torque per ampere (MTPA) controller could be used to increase the efficiency by limiting the copper loss. MTPA limits the copper loss and optimizes the efficiency, but this method does not consider the iron loss which includes hysteresis loss, eddy current loss and excess loss. References [6-10] model the iron loss of electrical machines, predict and analyze the possible parameters to iron loss, but finally do not give a clear and fixed strategy on optimizing iron loss. Reference [11] introduces an optimal method to get the optimal d axis current based on vector control strategy. However, for the iron loss resistance $R_{Fe}$, it does not introduce a method on how to get an accurate parameter and it is just fixed at rated operation.

For SC method, on the operation of fixed output power, it uses the online search technology to calculate the minimum system input power and then gives out the appropriate control signal for
maximum output power. Nowadays, golden section method search control (GSM-SC), gradient search technique and fuzzy logic search are used to find the optimal operation point [5, 12, 13]. Compared with LMC method, the system efficiency based on online SC method is higher under both rated operation and wide range operation. However, due to the time consumption of online SC and slow convergence, the system with online SC cannot meet some system requirements, for example, quick response and easy implementation.

Concerning the control methods, field-oriented control (FOC) and direct torque control (DTC) are the two most widely used control strategies for electric drive system [14]. Compared with FOC, the advantages of DTC are simple structure and quick response. However, for the efficiency optimization, DTC is not widely investigated or analyzed as much as FOC. Thus, in this paper, DTC method is analyzed. And for the efficiency optimization strategy, in order to meet the vehicle system requirement of quick response and wide range operation, the LMC method is better than SC method. Due to the particularity of the special IPMSM which is called low cost (LC) motor as shown in Fig.1 [3], the traditional estimation methods of iron loss cannot be used. In this paper, a proposed corporation between analytical method and FEM will be used to achieve the accuracy of the loss model by taking into account the influence of new topology of LC motor and improve the system efficiency. Which means the inverter harmonics and non-linear machine parameters will be considered.

The contents of this paper are organized as follows. In section I, two different d-q equivalent machine circuits with electrical loss of IPMSM are presented and one accurate iron loss model is introduced. In section II, the theoretical comparison between LMC and MTPA is analyzed; the expression of optimal reference stator flux for minimum electrical loss is also proposed. Section III shows the proposed methods to improve the system efficiency. Section IV gives the particularity of LC motor and analyzes the experiment results. Final conclusions are given in section V.

I. Model of LC Motor

The so called LC motor is a 12-teeth/10-poles concentrated winding interior permanent magnet synchronous machine (IPMSM)[15]. The cross-section of a prototype version is shown in Fig.1. Fig.2 shows the comparison of power losses between LC motor and conventional IPMSM. Due to the special double-layer concentrated winding and special topology, the LC motor has the following advantages:

- Low cost (simple manufacturing)
- High efficiency (e.g. short end winding, low copper loss, low cogging torque and low torque ripple)
- High energy density (compact design)

In the synchronous reference frame (d-q), the voltage equation and equivalent circuit for IPMSM can be expressed as equ.(1):
\[
\begin{align*}
\begin{cases}
    u_d &= R_i \cdot i_d + \frac{d\psi_d}{dt} - \omega \cdot \psi_q \\
    u_q &= R_i \cdot i_q + \frac{d\psi_q}{dt} + \omega \cdot \psi_d \\
\end{cases} \\
\psi_d &= L_d \cdot i_d + \psi_f \\
\psi_q &= L_q \cdot i_q
\end{align*}
\]

(1)

(2)

Where:
- \(u_d, u_q\) are the stator voltages on d-q reference frame;
- \(i_d, i_q\) are the stator currents on d-q reference frame;
- \(i_{\alpha}, i_{\beta}\) are the stator currents on \(\alpha-\beta\) reference frame;
- \(L_d, L_q\) are the inductances on d-q reference frame;
- \(\psi_f\) is the flux linkage of permanent magnet;
- \(\psi_s\) is the flux linkage of stator winding;
- \(\psi_d, \psi_q\) are the stator flux linkages on d-q reference frame;
- \(\omega_e\) is the electrical angular speed of rotor;
- \(R_s\) is the phase resistance.

Based on the equivalent circuit, reference [7, 12, 16] introduce the equivalent circuits of parallel model which include iron loss, as shown in Fig.3. \(R_{Fe}\) is the iron loss resistance; \(R_{PM}\) is the PM loss resistance; \(i_{loss-d}\) and \(i_{loss-q}\) are the iron loss and PM loss equivalent current of d and q equivalent circuit.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig3.png}
\caption{Equivalent circuit of IPMSM in d-q reference frame including losses. (a) Equivalent circuit of d axis. (b) Equivalent circuit of q axis.}
\end{figure}

From the equivalent circuit in Fig.3, on steady state operation, the voltage and current will be DC signals. The iron loss and copper loss can be expressed as following:

\[
P_{cu} = \frac{3}{2} R_i \left( \frac{\psi_d - \psi_f}{L_d} \right)^2 + \left( \frac{\psi_q}{L_q} \right)^2
\]

(3)

\[
P_{Fe} + P_{PM} = \frac{3}{2} \frac{\omega_e^2}{R_{Fe} + R_{PM}} (\psi_d^2 + \psi_q^2)
\]

(4)

Based on \(R_{Fe} + R_{PM} > R_s\), the equivalent circuit can be simplified and reference [17] introduces a simple circuit including iron loss, as shown in Fig.4. The structure of the circuit changes form parallel-series to parallel.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig4.png}
\caption{Simplified equivalent circuit of IPMSM in d-q reference frame including losses. (a) Equivalent circuit of d axis. (b) Equivalent circuit of q axis.}
\end{figure}
From the equivalent circuit in Fig.4, the iron loss and copper loss can be expressed as following. It can be seen that the solution and the implementation are much simpler than the traditional loss model, especially for the losses which are calculated by FEM, e.g. the iron loss and PM loss equivalent resistance can be get through iron loss, PM loss and equivalent d-q voltage. Here has to remind that the parallel structure or the simplified circuit is used to support the losses calculation based on FEM.

\[ P_{cu} = \frac{3}{2} R_c (i_{i_d}^2 + i_{i_q}^2) \]  
\( \text{(5)} \)

\[ P_{Fe} + P_{PM} = \frac{3}{2} (R_{Fe} + R_{PM}) (i_{Loss_d}^2 + i_{Loss_q}^2) \]
\[ = \frac{3}{2} (R_{Fe} + R_{PM}) (u_d^2 + u_q^2) \]  
\( \text{(6)} \)

II. Loss Model Control based on DTC

Loss minimum control based on current control has been widely analyzed by many researchers, and the loss function which includes copper loss and iron loss has been proved to be a convex function of \( i_{ad} \) [11]. Thus, through the first-order differential, the minimum loss of drive system can be achieved as following:

\[ \frac{\partial}{\partial i_{ad}} (P_{cu} + P_{Fe}) = 0 \]  
\( \text{(7)} \)

\[ i_{ad-optimal} = \frac{\omega d L_a (R_{Fe} + R_{PM}) \psi_f}{R_{Fe} R_{PM} + \omega d^2 L_a (R_{Fe} + R_{PM})} \]  
\( \text{(8)} \)

Compare with FOC, the principle of DTC method is controlling the output of electrical machine by adjusting the torque and stator flux. Thus the LMC method based on DTC method should find out the optimal stator flux of minimum loss. Based on d-q reference frame and Fig.3, the relationship between d and q axis flux can be described as following:

\[ \psi_q = \frac{T_e}{3 p (\psi_f L_q - (L_f - L_q) \frac{\psi_d - \psi_f}{L_d L_q})} \]  
\( \text{(9)} \)

Substituting equ.\( (9) \) into equ.\( (3) \) and equ.\( (4) \), the copper loss, iron loss and PM loss become the function of d axis flux. And the d axis flux has been proved to be the convex function of machine losses. Thus, based on equ.\( (11) \) and Ferrari’s solution, the optimal reference stator flux can be achieved.

\[ \frac{\partial^2 (P_{Fe} + P_{PM} + P_{cu})}{\partial (\psi_d)^2} > 0 \]  
\( \text{(10)} \)
Thus form equ. (11), the function of copper loss and iron loss has been proved to be a convex function of $\psi_d$, and the loss corresponding to d axis flux at constant speed is shown in Fig.5. It can be seen that there should be an optimal flux point $\psi_{od}$ with minimum loss. However, in practice, both of the application of BEVs and HEVs, wide range of speed and torque regulation are necessary. At low speed range, the popular MTPA is used, because the iron loss and PM loss can be assumed as proportional to the change rate of flux density, compared with copper loss, the iron loss and PM loss under low speed is very small, thus the neglect of iron loss and PM loss is reasonable. As shown in Fig.6, red and blue lines (solid line and dotted line) represent the machine losses; the small circuits mean the minimum loss points. It can be seen that the different between minimum loss points under 1000rpm and different torque is very small. However, compared with the iron loss and PM loss under low speed, the losses in high speed become a main component of machine losses. So in this paper, due to the application (BEVs and HEVs), e.g. in order to make motor run always with high efficiency under various conditions, this paper proposes an accurate and practical LMC approach for DTC to operate the machine. The influence of iron loss and PM loss to the LMC and MTPA is analyzed in Fig.6. The circus on the lines represents the minimum loss points.

From Fig. 6, it can be seen that the machine losses which include copper loss, iron loss and PM loss are different under different running points. However, if compare the optimal points (the circuit on lines) of the total machine losses at 1000rpm & 1Nm with the points at 1000rpm & 3Nm, it can be found that the difference of optimal points with or without iron loss and PM loss at 1000rpm is very small. In this condition that low speed running points, the iron loss and PM loss could be ignored and
MTPA is enough for efficiency optimization. When analyze the optimal points of the total machine losses at 1000rpm & 1Nm with the points at 3000rpm & 1Nm, it can be seen that the difference of optimal points with or without iron loss and PM loss at 1000rpm is big and cannot be neglected. Thus in the wide running range, LMC is good for the efficiency optimization.

Examples of copper loss and iron loss corresponding to different speed, torque and reference stator flux are also analyzed and shown in Fig.7 and Fig.8. Obviously, optimal efficiency points under different speed and different reference stator flux are feasible.

Due to the copper loss and iron loss, the d axis flux is a convex function; the optimal d axis flux or stator flux can be obtained from the following solution. Based on equ.(11) and Ferrari’s solution, the optimal reference stator flux can be achieved. The optimal reference stator flux can be obtained through equ.(12) and Fig.9 shows the optimal command flux based on variable speed and torque.

\[
\frac{\partial (P_{\text{Fe}} + P_{\text{PM}} + P_{\text{cu}})}{\partial (\psi_{od})} = 0
\]

\[
\psi_{st} = \sqrt{\psi_{od}^2 + \psi_{eq}^2}
\]

![Fig.7.Copper loss and iron loss based on different reference stator flux and torque at 1000 rpm.](image1)

![Fig.8.Copper loss and iron loss based on different reference stator flux and speed with constant torque.](image2)

![Fig.9.Optimal reference flux under variable torque and speed](image3)
III. Improvement of LMC

In practice, due to the influence of the control strategy and the characteristics of the inverter itself, the power supply of AC machine is always not ideal AC current or voltage, the output current of inverter always includes harmonics. According to the experimental results, Fig.10 shows the FFT analysis of inverter output current based on DTC. In order to improve the accuracy of machine loss model, the responding harmonics under different control strategies are injected in the ideal AC source of 2D-FEM. Thus, the 2-D FEM of LC machine does not only consider the harmonics which are produced by the machine itself (for example the machine topology), but also includes the current harmonics produced by the inverter. By increasing the accuracy of the voltage source of FEM model, the iron and PM losses including inverter harmonics are much more accurate than the losses without taking into account inverter harmonics. The influence of the harmonics to the machine losses is analyzed and shown in Fig.11.

![Fig.10. Phase current and FFT analysis based on DTC with LMC](image)

![Fig.11. Iron and PM losses with and without inverter harmonics based on 2D-FEM](image)

On the other hand, due to different operation points, the characteristics of machine parameters are non-linear. Based on FEM, Fig.12 and Fig.13 show the d-q inductance of LC motor under different current conditions. In order to improve machine efficiency based on LMC, in the control strategy, the non-linear inductance has been applied and the influence of non-linear machine parameters to LMC has been investigated, as shown in Fig.14. The mesh represents the optimal reference stator flux by taken into account the non-linear inductances. The surface represents the optimal reference stator flux by taken into account the linear inductances.
IV. Experiment Results

In this paper, based on the aim of efficiency optimization, the key point dynamic drive performance of the proposed DTC-LMC for LC motor is achieved and analyzed in Fig.17. Then the optimized motor efficiency is shown in Fig.18. The parameters and test bench of LC motor are shown in Table.I and Fig.15. The control strategy is shown in Fig.16.

Table.I. Parameters of LC motor used in the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pole pairs</td>
<td>5</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>$R_s$ 18mΩ</td>
</tr>
<tr>
<td>d axis inductance</td>
<td>$L_d$ 0.05mH</td>
</tr>
<tr>
<td>q axis inductance</td>
<td>$L_q$ 0.095mH</td>
</tr>
<tr>
<td>Permanent magnet flux</td>
<td>$\psi_f$ 7.07mVs</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>$U_{dc}$ 12V</td>
</tr>
<tr>
<td>Rated torque</td>
<td>$T_N$ 2Nm</td>
</tr>
</tbody>
</table>

Fig.14. Optimal reference flux with and without nonlinear inductance

Fig.15. The practical LC motor.
Regarding the effectiveness of DTC-LMC, the system efficiency is the final motivation. However, at the first step, compared with efficiency optimization, the drive performance of DTC-LMC is the most important destination. Fig.17 shows the startup characteristics of DTC-LMC. The step reference speed is from 0 to 1000rpm. Which shows that during torque response process, both of the zero voltage vectors are not selected, e.g. voltage vector 111 and 000. It means the fast torque response has been kept.

Fig.17. The startup characteristics of torque response: Ch1(blue):Reference speed 400rpm/div; Ch2(green):Actual speed 400rpm/div; Ch3(red):Actual electrical torque 0.5Nm/div; Ch4(pink):Switching state (1 and 8 mean zero voltage vectors, 2-6 mean non-zero voltage vectors).

Fig.18. System efficiency based on DTC-LMC.
V. Conclusion

From the theoretical analysis, the proposed efficiency optimization based on DTC is investigated and analyzed by simulation and experiment. Regarding the system cost, the LC motor is introduced and used. The experiment results verify the dynamic response of DTC-LMC, e.g. during torque response process, all the zero voltage vectors are not selected, which is an obviously advantage of DTC. It can also mean that the LMC nearly has no influence to the drive performance. By taking into account the inverter harmonics and nonlinear machine parameters, both of the accuracy of the LMC and machine efficiency are improved.

REFERENCES


