Hybrid Loss Minimization Control For Dual Three-phase Linear Induction Motor

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Abstract. Dual three-phase linear induction motor has harmonic losses that cannot be included in the loss-flux model in the z₁-z₂ subspace obtained by the generalized Clarke transform. The loss model of α-β subspace is not optimal for obtaining the reference flux. To solve this problem, losses in harmonic subspace was analyzed, and then a hybrid loss minimization control strategy was proposed. Based on the loss model that considers the end effect in the d-q subspace (transformed from α-β subspace), suboptimal flux linkage calculated by the model is set as the starting point of search controller, and optimal operating point could be obtained. Finally, the simulation results show that the strategy has better response performance than the traditional search method, and there is a certain loss reduction under various working conditions, especially at light load (0.2pu, 5 m/s), there is about 48.2% loss reduction.

1. Introduction
In recent decades, the application of multi-phase linear induction motors (LIM) has gradually increased, it is used in rail transportation, elevators, electromagnetic emission and aerospace. On the one hand, it combines the advantages of multi-phase system with high reliability, low thrust ripple, low device stress and the advantages of linear motor with high power density and high precision. On the other hand, the structure of the linear motor inevitably brings the air gap and the edge effect, so there is a higher loss [1], and multiphase systems are more complex in control and analysis [2].

The current minimum loss technology is mainly divided into offline and online. The former is used in the design and production stages, while the latter is focused on control strategies. The loss minimization control (LMC) strategy is divided into three types: loss-model-based, search-based, and hybrid [3]. Loss model-based strategy has a good response to load changes, but it also has a large dependence on system parameters, so it requires high accuracy of the model. The search controller (SC) measures the input and output power of the system without a loss model, but it responds slowly to changes, has convergence problems, and has large thrust fluctuations during adjustment. A suitable search starting point can reduce these effects. References [4-8] proposed loss models for rotating induction motors (RIM). In [8] the inverter parameters are fitted in sections and added to the motor loss model to establish a system-level loss model. A loss model considering machine loss, filter resistance, DC bus loss, and inverter loss is established in [5]. However, due to end effects of LIM, these RIM's loss model cannot be used directly. References [9-12] have established LIM loss models that consider the end effects. The LIM models are all developed on the basis of [13], using iron loss branches in parallel with the magnetizing inductance, which is more complicated. In contrast, SC strategies does not
depend on machine parameters, so most of them can be commonly used in LIM and RIM [14-16]. Loss composition of the six-phase RIM drive system was analyzed in detail in [14], and a direct torque control strategy based on the search control method was proposed.

For six-phase linear induction motors (6PLIM) using two sets of three-phase windings with a phase shift of \(30^\circ\), in order to simplify the control, a generalized Clark transform is often used to decompose them into three mutually orthogonal subspace \((\alpha, \beta, z_1-z_2, \omega_1-\omega_2)\). And control the motor in the \(\alpha-\beta\) subspace in the same way as the three-phase LIM. Among them, although the \(z_1-z_2\) subspace does not participate in electromechanical energy conversion, there is harmonic loss, because the three subspaces are orthogonal, and the losses in different subspaces cannot be combined into the same loss-flux model, so loss model methods cannot calculate accurately [14].

The structure of this article is as follows. In section II, based on the improved end effect model of 6PLIM [2], a suboptimal loss model for indirect field-oriented control (IFOC) is proposed. Then the model is combined with a SC method to propose a hybrid LMC strategy in section III. In section IV, the simulation results under various working conditions are presented, especially compare under light load condition.

2. Mathematical Model and Loss Analysis of 6PLIM

2.1. Mathematical Model

For common dual three-phase motors with a phase shift of 30 electrical degrees spatially between two sets of three-phase windings, it is customary to decouple six-dimensional vectors into three orthogonal subspaces through a generalized Clarke transform[17]. Then rotation transform the \(\alpha-\beta\) subspace to the synchronous d-q subspace, which is the only subspace for electromechanical energy conversion. Considering the loss of dynamic end effect, the equivalent circuit of LIM in synchronous d-q axis is shown in Fig. 1. In the figure, \(R, L, i, u, \) and \(\Psi\) are resistance, inductance, current, voltage, and flux, respectively. Where \(r\) and \(s\) in the subscripts represent the primary and secondary of the LIM, respectively, and \(d\) and \(q\) represent the equivalent d- and q-axis components of voltage, current, and flux. Moreover, \(L_{ls}, L_{lr} \) and \(L_m\) are the primary leakage inductance, the secondary leakage inductance, and the magnetizing inductance. \(K_e, K_r\) are correction coefficients for dynamic end effect, they are described in Appendix and detailed in [2].

![Fig 1. LIM equivalent circuit on the d-q axis considers the dynamic end effect](image)

Specifically, define \(L_{me}\) and \(R_{re}\) to simplify the expression:
All the voltage and flux can be derived from the equivalent circuit are as follows:

\[
\begin{align*}
L_{me} &= L_m K_e \\
R_{re} &= R_s K_r.
\end{align*}
\] (1)

Where \(\omega_{sl}\) and \(\omega_s\) are the slip and primary angular frequency, respectively. And \(p\) is the differential operator.

When the transformation of the model with principle of power invariance, the thrust can be expressed by:

\[
F = \beta L_{me} (i_{dr} i_{qs} - i_{qr} i_{ds}) = \beta \frac{L_{me}}{L_{me} + L_{ir}} \psi_{dr} i_{qs}.
\] (4)

Where \(\beta = \pi/\tau\), and \(\tau\) is the pole pitch.

2.2. Loss Model in d-q Subspace

The expression of total controllable loss of LIM in the d-q subspace can be written by the equivalent circuit as follows:

\[
P_{LIM} = R_s (i_{ds}^2 + i_{qs}^2) + R_s (i_{ds}^2 + i_{qr}^2) + R_{re} (i_{ds} + i_{dr})^2.
\] (5)

While flux saturation is not considered due to LIM is generally designed with low average flux density, under secondary field-oriented control, in steady-state each flux component can be regarded as a constant [9], where the secondary q-axis flux and the secondary d-axis current can be regarded as zero, which is expressed as:

\[
\begin{align*}
\psi_{qr} &= 0, \\
i_{dr} &= 0.
\end{align*}
\] (6)
The slip angular frequency can be derived from (3), (4), (6) as:

\[ \omega_{sl} = -\frac{R_s i_{qr}}{\psi_{dr}}. \]  

(7)

\[
\begin{align*}
    i_{ds} & = \frac{1}{L_{me}} \psi_{dr}, \\
    i_{qs} & = \frac{(L_{me} + L_{v})F}{L_{me} \beta} \psi_{dr}^{-1}, \\
    i_{qr} & = -\frac{F}{\beta} \psi_{dr}^{-1}. 
\end{align*}
\]

(8)

Substituting (8) into (5) can written the loss in d-q subspace as follows:

\[ P_{loss} = A_1 \psi_{dr}^2 + A_2 \psi_{dr}^{-2}. \]  

(9)

\[
\begin{align*}
    A_1 & = \frac{R_s + R_v}{L_{me}^2}, \\
    A_2 & = \left( \frac{F}{\beta} \right)^2 \left[ R_s + R_v \left( \frac{L_{v} + L_{me}}{L_{me}} \right)^2 \right]. 
\end{align*}
\]

(10)

As shown in Fig. 2, the point of minimum loss can always be found and calculated as the zero point of the loss-flux curve (calculation parameters in appendix). The suboptimal reference flux can be express as:

\[ \psi_{dr}^* = \sqrt[4]{\frac{A_2}{A_1}}. \]  

(11)

![Fig 2. Losses vs. flux under different loads at 10m/s in d-q subspace.](image)
2.3. Loss in z1 – z2 Subspace

Practice has proved that if only control d-q axis currents, under the traditional SVPWM, there are harmonics in the stator current of the six-phase motor[14]. Inverter output current waveforms with and without considering $z_1-z_2$ subspace harmonics at 5m/s and 0.2pu operating conditions are shown in Fig. 3.

![Inverter output current waveforms](image)

**Fig 3.** Inverter output current waveforms with and without considering $z_1-z_2$ subspace harmonics at 5 m/s and 0.2pu operating conditions. (a) without $z_1$-$z_2$ subspace harmonics. (b) considering $z_1$-$z_2$ subspace harmonics.

The model of 6PLIM in $z_1$-$z_2$ subspace could be deduced as:

\[
\begin{align*}
    v_{z1} &= \left( R_s + pL_{ts} \right) i_{z1}, \\
    v_{z2} &= \left( R_s + pL_{ts} \right) i_{z2}.
\end{align*}
\] (12)

And the loss $P_z$ can be written as follows [14]:

\[
P_z = \frac{1}{2} R_s \left( I_{z1}^2 + I_{z2}^2 \right) + \frac{1}{2} R_2 \left( I_{rz1}^2 + I_{rz2}^2 \right).
\] (13)

It is easy to find that the part of loss cannot be added to the d-q space loss model above. Although a number of SVPWM strategies have been proposed to reduce six-phase inverter harmonic loss [18-21], its impact is still cannot ignore.
3. Hybrid LMC Strategy of IFOC in the 6PLIM

3.1. SC Strategy with Golden Section Principle

When input and output power of the system is measured in real time, by changing the flux reference value within a small range, the optimal operating point within a certain range can be searched. The golden section principle is widely used in SC strategies for faster corresponding performance and less thrust ripple [22]. The flowchart of SC strategy is shown as Fig. 4.

![Flowchart of optimal flux SC strategy](image)

Where $h$ and $\sigma$ are permissible error and step of change in $\Psi_{dr}$ calculated by the golden section principle, and its value will decrease during every search step.
3.2. Topology of Hybrid LMC Strategy

For shorten the search time and reduce the thrust ripple, set the initial value of $\Psi_{dr}(0)$ to the suboptimal value calculated as (11). And the overall topology of the hybrid LMC strategy is as.

![Diagram of Topology of Hybrid LMC Strategy](image)

Fig 5. Topology of the hybrid LMC strategy

4. Simulation and Analysis

4.1. Light Load Condition

The traditional IFOC strategy needs to maintain a large magnetizing current to keep the flux constant. Therefore, the contrast of steady-state losses between proposed LMC and traditional IFOC strategy can be more obvious.

The simulation results of the machine using two strategies at 5m/s, 0.2pu are shown as Fig. 6 and Fig. 7. The simulation start with IFOC ($\Psi_{dr} = 0.85Wb$) and the proposed LMC is applied at 2 s.

![Graph of Change of inverter output currents](image)

Fig 6. Change of inverter output currents
It can be found that after switching to proposed LMC strategy, the inverter output currents amplitudes are reduced by about 50%, and the speed reaches the set value again after a slight fluctuation. Since the loss model is used to calculate the suboptimal flux linkage as the initial search value, the transient process is very short (about 0.1s), in contrast, the traditional SC strategy takes several seconds [3]. And the total loss under this light load is reduced from 680w to 330w (48.5%).

4.2. Various Conditions
In order to further test the improvement of the proposed LMC strategy under various speed and load conditions, the losses under different working conditions are shown in Fig. 8. The reference flux of IFOC strategy is set as 0.85 Wb.

It can be found that the total loss under both strategies tends to increase with increasing load and speed. In addition, because the motor is designed to have a minimum loss at the rated condition, when approaching the rated point, the given flux and the calculated optimal flux will approach the equivalent, that is, the difference between LMC and IFOC strategy will decrease. However, the efficiency of the IFOC strategy cannot be higher than the LMC strategy under all conditions.

It is considered that 6PLIM works in light and overload, and when the motor is used in high-power occasions, such as urban transit, a slight efficiency improvement has significant economic benefits.
5. Conclusion
A hybrid LMC strategy is proposed for minimize the total loss of 6PLIM with harmonic subspace that cannot be accurately modeled. An end effect loss model is used to greatly reduce the search range, and then the optimal reference flux linkage could be searched within one second, and the total power loss can be reduced by more than 45% under light load. Further, as simulation results show, no matter what the load and speed, this strategy always has a certain efficiency improvement.

6. Appendix

Table 1. Parameters of 6PLIM simulation model

| Symbols | Parameters | Value |
|---------|------------|-------|
| $U_N$   | Rated Voltage | 180 V |
| $N_p$   | Pole-pair number | 6 |
| $L_m$   | Magnetizing inductance | 0.0342 H |
| $L_{ls}$ | Primary leakage inductance | 0.0174 H |
| $L_{lr}$ | Secondary leakage inductance | 0.0043 H |
| $R_s$   | Primary resistance | 1.2 Ω |
| $R_r$   | Secondary resistance | 2.4 Ω |
| $\tau$  | Pole pitch | 0.15 m |
The correction coefficients $K_e$, $K_r$ can be written as follows:

\[
\begin{align*}
K_e &= \frac{1}{1+K_m}, \\
K_r &= K_1 + K_2, \\
K_m &= \frac{1}{Q} \left( 1 + \frac{S_m \mu_{Q,t} - S_t \mu_{Q,t}}{2\lambda} \right), \\
T_r &= \frac{L_m + L_r}{R_r}, \quad T_s = \frac{D}{V}, \\
Q &= \frac{T_s}{T_r} = \frac{DR}{V(L_m + L_r)}, \\
\lambda &= \sqrt{\frac{R_r}{2L_r}} - \frac{1}{L_rC}, \\
S_{1,2} &= -\frac{R_r}{2L_r} \mp \lambda.
\end{align*}
\]

\[
\begin{align*}
K_1 &= \frac{R_r^2}{4\lambda^2 L_r^2 T_r} \left[ \frac{e^{2\lambda r_t} - 1}{2S_1} + \frac{e^{2\lambda r_t}}{2S_2} - \frac{2e^{(S_1+S_2)r_t} + 2}{S_1 + S_2} \right], \\
K_2 &= \frac{R_r^2}{4\lambda^2 L_r^2 Q} \left[ \frac{1}{2} \left( e^{2\lambda r_t} + e^{2\lambda r_t} - e^{(S_1+S_2)r_t} \right) \right].
\end{align*}
\]

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