FOC for Loss Minimization of Induction Motor Using SVM

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Abstract
Field oriented control (FOC) can provide an ability to rapidly and accurately control torque and speed of induction motors (IM). However, at lower than rated loads, which is a condition that many machines experience for significant portion of their service life, the efficiency is greatly reduced. This paper describes the use of supported vector machine (SVM) to optimize the efficiency of IM drive. The approach eliminates the need of accurate math model and large computation complexity in traditional loss model controller (LMC). The new efficiency optimizing controller adjusts a magnetizing current component in vector controlled drives, which ensures a minimum loss to improve efficiency of the drive system especially when driving light load. The performance of the proposed drive is demonstrated through simulation in MATLAB/SIMULINK and compared the same with traditional FOC without LMC. Results show that there is considerable loss reduction and improvement in efficiency under light load condition using the method.

Key words: LOSS MINIMIZATION, SUPPORTED VECTOR MACHINE, FIELD ORIENTED CONTROL, EFFICIENCY OPTIMATION

1. Introduction
Induction motors have been widely used in various industries; especially three-phase IMs have consumed 60% of industrial electricity [1-3]. Because of advantage of vector controller, IM has a high efficiency at rated speed and torque, but motor efficiency decreases drastically at light loads. It takes considerable effort to improve their efficiency, especially used in pure electric vehicles (EVs) [4]. In order to ensure the dynamic performance of EVs, including acceleration and upgrade, peak power and peak torque values were designed very large. But the motor’s export power and torque have been able to reach less than a third of the peak values in the actual running. Actually the given magnetizing current keeping constant for the whole range of IM drives is one of the main causes of the low efficiency.

Many minimum loss control schemes based on vector control of IM drives have been
Automatization

reported in literature [5-8]. There are two categories of the control strategy to improve motor efficiency. One is the search controller [9]. The other is loss model based controller (LMC) [10-14]. The search controller is the online power search optimization method which uses the measured input power to the motor and perturbs control variables until the measured power is minimum value for a particular operating condition. It could appear with good justification that these efficiency improvement schemes find their greatest utility under steady and quasi-steady-state operating conditions. Waheeda Beevi M [15] and Rouabah Z [16] taking speed and load torque as input, adopted genetic algorithm to search the optimal magnetizing current. Kim [17] proposed a method that combined particle swarm algorithm and genetic algorithm to search the optimal magnetizing current. However important drawbacks of the search controller are the slow convergence and torque ripples. LMC is based on the accurate math model of the loss model. By complex computations, the magnetizing current or magnetizing flux is obtained with a minimum of loss. To avoid this, simplified model is needed in the practical applications to get the approximate optimal solution. But errors appear between approximate results and real results. Waheeda Beevi M [18] proposed an improved LMC to increase efficiency and power factor which achieved preferable dynamic performance and accuracy. Uddin M. N. [19] presented a new LMC considering leakage inductance on the rotor side to determine an optimum flux level. In short, LMC was fast and did not produce torque ripple. Moreover, many identification methods were combined to get better results. Kashem M.A. [20] proposed a new approach of distribution system reconfiguration for loss minimization. Yamamoto Shu [21] showed a novel loss minimization controller with inductance estimator.

We study, in this paper, the feasibility of the support vector machine (SVM) in loss minimization of IM described by the FOC model. The motor loss model takes into account the iron losses and copper losses. The SVM technique is applied to minimizing these IM losses and thus maximizing its efficiency by adjusting the magnetizing current to its optimal value. Simulation performances are presented and a comparative study is carried out between the results obtained by using SVM and the traditional vector control.

2. Loss model of IM

Fig.1 shows the steady state IM equivalent circuits in \(d\) and \(q\) axis. \(i_r\) is the sum of rotor current and \(i_{mr}\) is the current which is perpendicular to the magnetizing current \(i_{mr}\). \(\omega_1\) is the angular frequency of the stator. \(\omega\) is the electrical angle frequency. \(R_s\) is the stator equivalent resistance. \(R_r\) is the rotor equivalent resistance. \(L_s\) and \(L_r\) are stator and rotor inductance. \(L_{m}\) is mutual inductance.

The circuit illustrates decomposition of the stator current into the rotor flux-oriented components, \(i_q = i_{mr}\). \(i_q\) is related to control the torque developed by the motor, \(i_q = i_f + i_r\).

From Fig.1, the rotor current can be expressed as:

\[
i_r = \frac{R_{Fe}}{R_{Fe} + R_2} i_q - \omega \frac{L_m}{R_{Fe} + R_2} i_d
\]

Stator copper, rotor copper and iron losses dominate the overall power loss and total loss can be expressed in \(d-q\) coordinates by:

\[
P_{loss} = P_{Fe1} + P_{Fe2} + P_{Cu1} + P_{Cu2} = R_1(i_q^2 + i_r^2) + R_{Fe}(i_q^2 + i_r^2) + R_2 i_r^2
\]

The iron loss \(P_{Fe1}\) of IM includes the stator iron loss \(P_{Fe1}\) and rotor iron loss \(P_{Fe2}\). \(R_{Fe}\) is an equivalent resistance of the total iron loss. So the total power loss is given by

\[
P_{loss} = \ldots
\]
\[ p_{\text{loss}} = R_d i_d^2 + R_q i_q^2 \]  \hspace{1cm} (3)

\[ R_d = R_1 + \frac{\omega^2 L_m}{R_2}, \quad R_q = R_1 + \frac{R_{pL} R_2}{R_{pL} + R_2} \]

Where

The calculation formula of torque is derived by rotor field oriented control under the two-phase synchronous rotary coordinate.

\[ T_e = \frac{n_p L_m}{L_r} i_q \psi_2 \]  \hspace{1cm} (4)

Where \( n_p \) is the number of pole pairs, \( \psi_2 \) is the rotor flux, and \( T_e \) is the magnetic torque. In the steady state,

\[ \psi_2 = L_m i_d \]  \hspace{1cm} (5)

So the magnetic torque can be deduced by (6).

\[ T_e = k_i i_q i_d \]  \hspace{1cm} (6)

Where

So the total loss in the machine is given by

\[ p_{\text{loss}} = R_d i_d^2 + R_q \frac{T_e^2}{k_i i_d^2} \]  \hspace{1cm} (7)

For minimum power loss,

\[ \frac{\partial p_{\text{loss}}}{\partial i_d} = 0 \]  \hspace{1cm} (8)

Thus the optimum value of magnetizing current is given by

\[ i_{\text{m}_0 \_\text{opt}} = i_d = \sqrt{\frac{R_e T_e^2}{k_i R_d}} \]  \hspace{1cm} (9)

Meanwhile the total loss reached minimum.

From (9), we get the relationship between \( i_{\text{m}_0 \_\text{opt}} \) and \( T_e, R_d, R_q, k_i \).

3. Mechanism of Loss Minimization

3.1. Structure of Control System

The structure of the overall control system proposed is shown in Figure 2. The system includes three-phase induction motor, three-phase inverter, space vector pulse width modulation (SVPWM), field oriented control (FOC) and three controllers. The controllers adopt cascade control, including a speed loop and two current loops. Series structure can guarantee the system’s ability of resisting disturbance and improve its set point response ability, the final control objective is to strengthen speed and torque dynamic tracking property. Based on the above Loss Minimization algorithm, the proposed loss minimization controller (LMC) is developed. LMC takes the speed, torque as inputs and outputs the optimum magnetizing current.

3.2. SVM optimization procedure

The SVM algorithm was a nonlinear generalization of the generalized portrait algorithm developed in Russia by Vapnik and others in 1963. SVM is a learning system that uses an adaptive margin-based loss functions, implements the structural risk minimization principle, and solves nonlinear problems in high dimensional feature space through kernel functions linearly, which yields prediction functions that are expanded on a subset of support vectors.

Function model based LMC of IM is established.

\[ y = f(x_1, x_2) \]  \hspace{1cm} (10)

Where \( x_1 \) is torque, \( x_2 \) is speed, \( y \) is optimal magnetizing current.

Equation (10) shows a complex relation of nonlinear function. The important claim is we don’t know the actual formula. So use the...
Automatization

nonparametric estimation as approximation. SVM is a new nonlinear modeling method which is suitable for solving small samples and high dimension modeling problems. Either can implement approximating nonlinear functions by arbitrary accuracy.

Consider the problem of approximating the following data set:
\[ D = \{(x_i, y_i)\}, x_i \in \mathbb{R}, y_i \in \mathbb{R} \]  \hspace{1cm} (11)

Where \( i = 1, 2, \ldots, d \).

The regression estimation model becomes
\[ f(x) = \sum_{i=1}^{d} (\alpha_i - \alpha_i^*) (x | x_i) + b \]  \hspace{1cm} (12)

Where \( \alpha_i \) is Lagrangian multiplier, \( b \) is the domain.

Modeling of IM is nonlinear problem. However, it can be converted to a higher dimensional space of linear problems and linear regression in high dimensional space. The actual calculation is only related to inner product operation. Using the integral operator kernel function instead of dot product, Equation (12) can be re-formulated as
\[ f(x) = \sum_{i=1}^{d} (\alpha_i - \alpha_i^*) K(x, x_i) + b \]  \hspace{1cm} (13)

The training stage of SVM is given in Fig.3. Select a Gaussian kernel function.
\[ K(x, x_i) = e^{-\frac{(x-x_i)^2}{2\sigma^2}} \]  \hspace{1cm} (14)

\( \sigma, b, d \) are kernel parameters for each kernel function and these parameters affect the performance of SVM.

Figure 3. Training stage of support vector machine

In Figure 4, the flow chart of the SVM parameter adjusting is described. The initial SVM model can be identified using the input-output data obtained from the closed-loop operation of FOC with traditional LMC.

4. Simulation Results

To demonstrate the efficiency of the proposed LMC method, this paper establishes FOC model of induction motor control system as Figure 2 by the SIMULINK of software MATLAB. The new SVM algorithm used S-Function model to implement. The discrete time step is \( 2 \mu s \). The parameters of the induction motor are given as: rated power \( P = 100kW \), rated voltage \( U = 600V \), rated frequency \( f_N = 50Hz \), rated load torque \( T_L = 1000N\cdot m \), number of pole \( n_p = 3 \), \( R_s = 0.016\Omega \), \( R_r = 0.035\Omega \), \( L_s = L_r = 1.666 \times 10^{-4}H \), \( L_m = 6.27mH \).

In this paper, all the feature elements and target values are scaled so that they fall into the range of \([1, 2]\). There are two design parameters that need to be tuned, i.e. \( C \) and \( \sigma \). For convenience, a composite hyper parameter \( g = \frac{1}{2\sigma^2} \) is used instead of \( \sigma \). Thus the finer search was made by K-CV method, which is obtained at best \( C = 1, g = 8 \). Best Cross Validation MSE=0.00027917. Mean squared error = 4.78407e-005, Squared correlation coefficient = 0.999518. Figure 5 shows the choice of parameters of SVM in 3D view. The comparison between original data and regression predicted data is given by Figure 6.
After generating the loss model based on SVM, the model can be used to drive the IM in FOC.

Figure 7– Figure 9 shows that the comparison between the LMC-based-on-SVM controller and the traditional FOC controller in the case of 1000 rpm reference speed and 200 N·m lightly load torque. It can also be seen from Figure 7 that, when startup, the new controller method has gives a shorter settling time but a larger overshoot. Therefore, the new controller is more applicable to be used in the steady state. Fig.8 shows effect on the output torque performance is the same by both controllers. Figure 9 compares the efficiency of both controllers and result verifies the effectiveness of the proposed method.

5. Conclusions
The derivation of SVM to predict the magnetizing current of FOC has been accomplished in this paper. The proposed loss-model controller is developed considering main losses in the machine. The performance has been tested by simulation. Drive performance has been improved in terms of power saving compared to without the LMC in drive.

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