FOC for Loss Minimization of Induction Motor Using SVM

Fang Xie[1, 2]

[1]*School of Electrical Engineering and Automation,*
Anhui University, Hefei230000, Anhui, China
[2]*Anhui Province Laboratory of Electrical Economize and Safety,*
Anhui University, Anhui, China

Qunjing Wang

National Engineering Laboratory of Energy-Saving Motor & Control Technology,
Anhui University, Hefei230000, Anhui, China

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

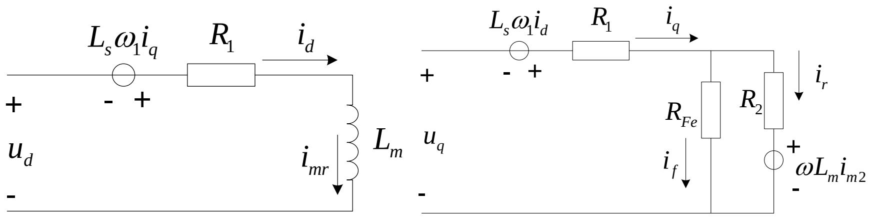
Induction motors have been widely used in various industries; especially three-phase IMs have consumed 60% of industrial electricity [1-3]. Because of advantage of vector controller, IM has a high efficiency at rated speed and torque, but motor efficiency decreases drastically at light loads. It takes 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 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_f is the iron current which is perpendicular to the magnetizing current i_{mr}. ω_1 is the angular frequency of the stator. ω is the electrical angle frequency. R_1 is the stator equivalent resistance. R_2 is the rotor equivalent resistance. L_s and L_r are stator and rotor inductance. L_m is mutual inductance.



(a) d-axis equivalent circuit (b) q-axis equivalent circuit

Figure 1. Steady state IM equivalent circuit in FOC

The circuit illustrates decomposition of the stator current into the rotor flux-oriented components, $i_d = i_{mr}$.

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:

$$i_r = \frac{R_{Fe}}{R_{Fe}+R_2} i_q - \omega \frac{L_m}{R_{Fe}+R_2} i_d \tag{1}$$

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

$$\begin{aligned} p_{loss} &= p_{Fe1} + p_{Fe2} + p_{Cu1} + p_{Cu2} \\ &= R_1(i_d^2 + i_q^2) + R_{Fe}(i_q - i_r)^2 + R_2 i_r^2 \end{aligned} \tag{2}$$

The iron loss p_{Fe} 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

$$p_{loss} = R_d i_d^2 + R_q i_q^2 \quad (3)$$

Where $R_d = R_1 + \dfrac{\omega^2 L_m^2}{R_{Fe} + R_2}$, $R_q = R_1 + \dfrac{R_{Fe} R_2}{R_{Fe} + R_2}$。

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

$$T_e = \frac{n_p L_m}{L_r} i_q \psi_2 \quad (4)$$

Where n_p is the number of pole pairs, ψ_2 is the rotor flux, T_e is the magnetic torque. In the steady state,

$$\psi_2 = L_m i_d \quad (5)$$

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

$$T_e = k_t i_d i_q \quad (6)$$

Where $k_t = \dfrac{n_p L_m^2}{L_r}$.

So the total loss in the machine is given by

$$p_{loss} = R_d i_d^2 + R_q \frac{T_e^2}{k_t^2 i_d^2} \quad (7)$$

For minimum power loss,

$$\frac{\partial p_{loss}}{\partial i_d} = 0 \quad (8)$$

Thus the optimum value of magnetizing current is given by

$$i_{mr\_opt} = i_d = \sqrt[4]{\frac{R_q T_e^2}{R_d k_t^2}} \quad (9)$$

Meanwhile the total losses reached minimum.

From (9), we get the relationship between i_{mr_opt} and T_e, R_d, R_q, k_t.

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.

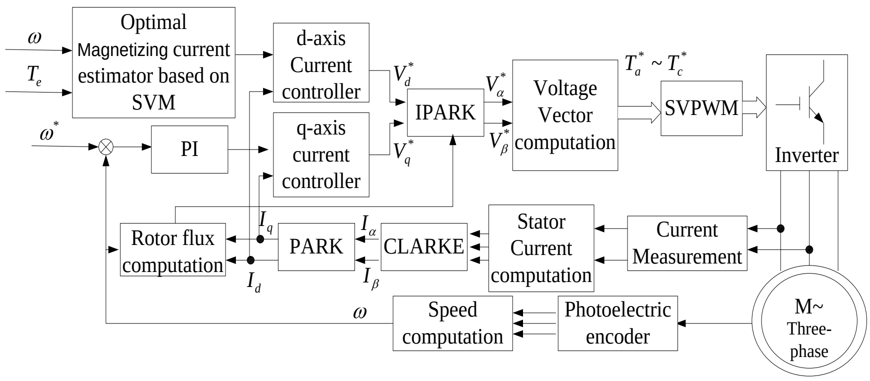


Figure 2. Efficiency optimization simulation model of FOC based on SVM

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 mimimization 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.

$$y = f(x_1, x_2) \quad (10)$$

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 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:

$$D=\{(x_i,y_i)\},x_i\in R,y_i\in R \tag{11}$$

Where $i=1,2,\cdots,d$.

The regression estimation model becomes

$$f(x)=\sum_{i=1}^{d}(\alpha_i-\alpha_i^*)(x_i\cdot x_j)+b \tag{12}$$

Where α_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

$$f(x)=\sum_{i=1}^{d}(\alpha_i-\alpha_i^*)K(x_i,x_j)+b \tag{13}$$

The training stage of SVM is given in Fig.3. Select a Gaussian kernel function.

$$K(x_i,x_j)=e^{-\frac{\|x_i-x_j\|^2}{2\sigma^2}} \tag{14}$$

σ, b d are kernel parameters for each kernel function and these parameters affect the performance of SVM.

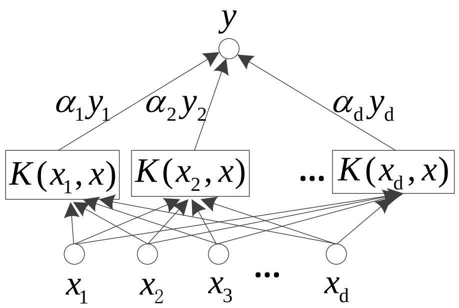


Figure 3. Training stage of support vector machine

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.

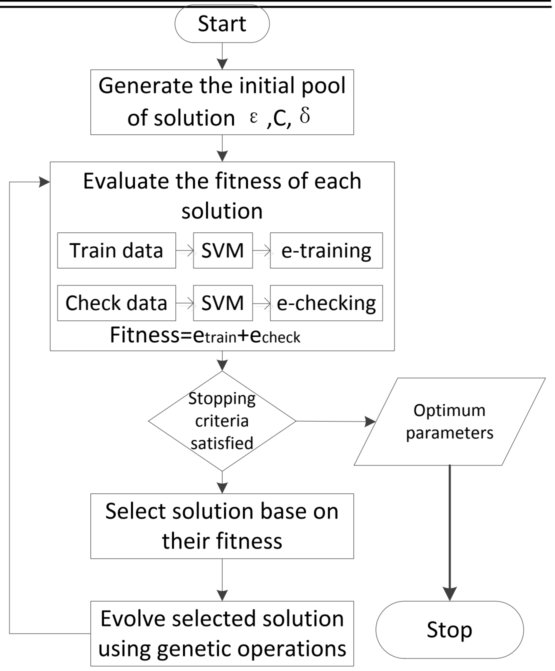


Figure 4. Parameter adjusting flowchart

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 $n_p=3$, $R_s=0.016\Omega$, $R_r=0.035\Omega$, $L_s=L_r=1.666\times10^{-4}H$, $L_m=6.27mH$.

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 σ. For convenience, a composite hyper parameter $g=\frac{1}{2\sigma^2}$ is used instead of σ. 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.

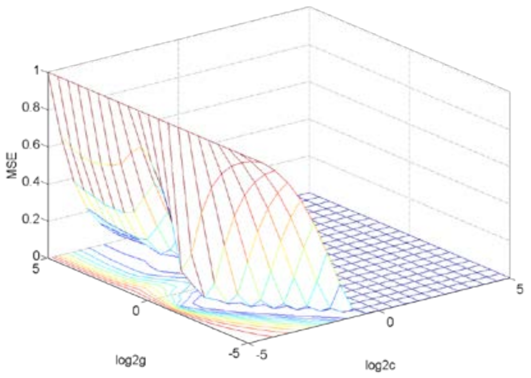


Figure 5. The choice of parameters of SVM (3D View)

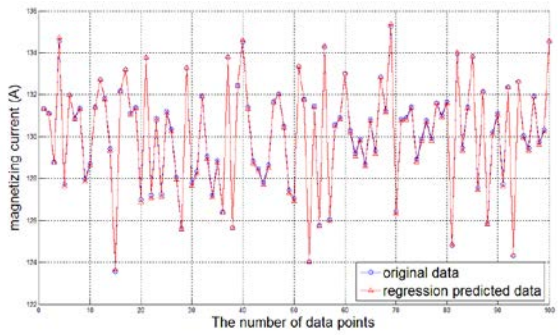


Figure 6. The comparison between original data and regression predicted data

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 $200N\cdot m$ 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.

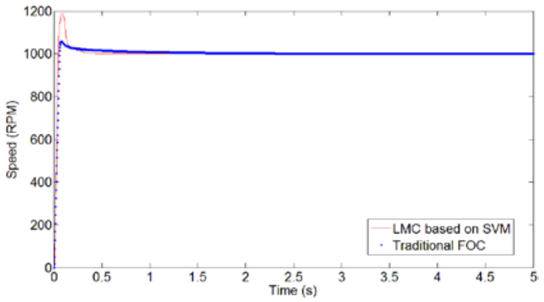


Figure 7. Waveform of Speed

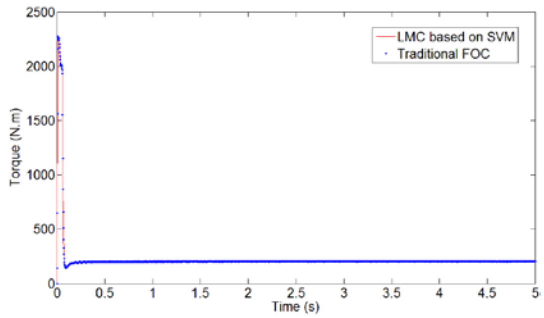


Figure 8. Waveform of Torque

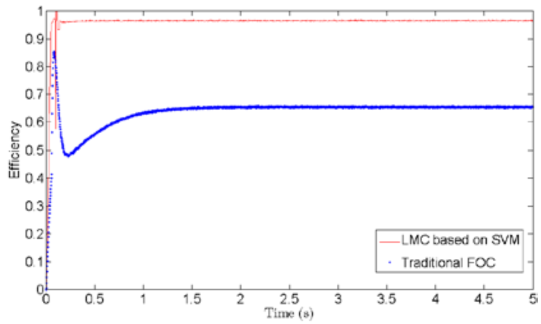


Figure 9. Waveform of Efficiency

Through design example, it can be seen the controller based on SVM could estimate the parameters accurately and achieve a perfect dynamic and static performance especially in the steady state. Besides, to overcome the disadvantage of large overshoot when startup, the new LMC should be adopted for steady state operation.

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.

6. Acknowledgements

This work was supported by the National Nature Science Foundation of China (No. 51177001, No. 61300056), Youth Foundation of Anhui University (No. 02303305(33050064)), 2014 Education Department of Anhui province key project (No. KJ2014A019). Thank for National Engineering Laboratory of Energy-Saving Motor and Control Technology, Anhui University and Anhui Province Laboratory of Electrical Economize and Safety.

References

1. Chandan Chakraborty, Yoichi Hori (2003) Fast efficiency optimization techniques for the Indirect Vector-Controlled Induction

motor drives. *IEEE Transactions on Industry Applications*, 39(4), p.p.1070-1076.

2. Pei Wen-hui, Zhang Cheng-hui, Cui Na-xin, Han Qi, Li Ke (2012) Loss-minimization Hamilton control of induction motor for electric vehicles. *Electric Machines and Control*, 16(4), p.p.1-7.
3. Bazzi Ali M., Krein Philip T. (2010) Review of methods for real-time loss minimization in induction machines. *IEEE Transactions on Industry Applications*, 46(6), p.p.2319-2328.
4. Khang Huynh Van, Arkkio Antero, Saari Juha (2012) Loss minimization for form-wound stator winding of a high-speed induction motor. *IEEE Transactions on Magnetics*, 48(12), p.p. 4874-4879.
5. E. Hussein, P. Mutschler (2010) Optimal flux loss model based speed sensorless control of Induction motor. *PEMD 2010 Power Electronics, Machines and Drives conference*, Brighton, UK, p.p.1-6.
6. Femandez-Bernal, A. Garcia-Cerrada, and R. Faure (2000) Model-based loss minimization for DC and AC Vector-Controlled Motors including core saturation. *IEEE Transactions on Industry Application*, 36(3), p.p. 755-763.
7. Zidani F., Nait Said M.S., Abdessemed R., Diallo D, and Benbouzid M.E.H. (2002) A fuzzy technique for loss minimization in scalar-controlled induction motor. *Electric Power Components and Systems*, 30(6), p.p.625-635.
8. Rivera Dominguez Jorge, Mora-Soto Christian, Ortega-Cisneros Susana, Raygoza Panduro, Juan Jose, Loukianov Alexander G. (2012) Copper and core loss minimization for induction motors using high-order sliding-mode control. *IEEE Transactions on Industrial Electronics*, 9(7), p.p.2877-2889.
9. Jie Li et al. (2005) Efficiency optimization of induction machines based on Fuzzy search controller. *Proceeding of the Fourth International Conference on Machine Learning and Cybernetic*, Guangzhou, China, pp.2518-2522.
10. M. Nasir Uddin, Sang Woo Nam (2008) New online loss-minimization-based control of an Induction motor drive. *IEEE Transactions on Power Electronics*, 23(2), p.p.926-933.
11. M. Waheeda Beevi, A. Sureshkumar and Mano Mary Kuriakose (2010) Loss minimization control of vector controlled induction motor drives. *International Conference on communication and computing (ICCC 2010)*, Nanning, China, p.p.182-187.
12. Cavallaro C, Antonino O D T, Rosariom (2005) Efficiency enhancement of permanent magnet synchronous motor drives by online lossminimization approaches. *IEEE Trans on Industrial Electronics*, 52, p.p.1153-1160.
13. K. Yamazaki, A. Abe (2007) Loss analysis of interior permanent magnet motors considering carrier Harmonics and magnet eddy currents using 3-D FEM. *IEEE International Electric Machines and Drives Conference*, Antalya, Turkey, p.p. 904-909.
14. James E. Kettlewell, Narayan C. Kar (2010) Steady-state Performance analysis of interior permanent magnet synchronous machines using the classical D-Q model. *XIX International Conference on Electrical Machines*, Rome, Italy, p.p.1-5.
15. Waheeda Beevi M, Dr.A Sukesh Kumar, Sibin H S. (2012) Loss minimization of vector controlled induction motor drive using Genetic algorithm. *International Conference on Green Technol*ogies, Bremen, Germany, p.p.251-257.
16. Rouabah Z., Abdelhadi B, Anayi F., Zidani F. (2008) On-line losses minimization of induction motor vector control. *Archives of Electrical Engineering.* 60(3), p.p.257-268.
17. Kim Dong Hwa, Hirota Kaoro. (2008) Vector control for loss minimization of induction motor using GA-PSO. *Applied soft computing Journal*, 8(4), p.p.1692-1702.
18. Waheedabeevi M, Dr.A.Sukesh kumar, NithinS Nair (2012) New online loss-minimization-based control of scalar and vector-controlled induction motor drives. *IEEE International Conference on Power Electronics, Drives and Energy Systems*, Bengaluru, India, p.p.16-19.
19. Uddin M.Nasir, Nam Sang Woo (2008) New online loss-minimization-based control of an induction motor drive. *IEEE Transactions on Power Electronics*, 23(2), p.p.926-933.
20. Kashem M.A., Jasmon G.B., Ganapathy (2000) New approach of distribution system reconfiguration for loss minimization. *International Journal of Electrical Power and Energy System*, 22(4), p.p.269-276.
21. Yamamoto Shu, Hirahara Hideaki, Adawey John B., Ara Takahiro, Matsuse Kouki (2013) Maximum efficiency drives of synchronous reluctance motors by a novel loss minimization controller with inductance estimator. *IEEE Transactions on Industry Applications*, 49(6), p.p.2543-2551.