New Loss Minimization Controller for Induction Motor drives

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Abstract

This paper proposes a new loss minimization controller (LMC) for induction motor drive. The proposed LMC presents a strategy to minimize the total power losses of induction motor (IM), which is based on simplified equivalent circuit and simplified model of IM. The proposed controller using the field oriented control (FOC) method is to determine an optimal rotor flux for obtaining the minimum total power losses and higher efficiency. Simulation and experimental results are given to validate the effectiveness of the proposed method.

1. Introduction

Three-phase induction motors (IM) are extensively used in industry and consume more than 50% of industrial electricity. To obtain the high power usage efficiency, we should reduce the total power losses which include grid loss, converter loss, motor loss and transmission loss. To overcome these problems, high quality materials and excellent design procedures in manufacturing processes are applied to minimize the electrical system loss. However, converter loss and motor loss are significantly dependent on control strategies, especially when the motor operates at light load conditions.

The control strategies to improve motor efficiency can be divided into two categories: 1) search controller (SC), 2) loss minimization controller (LMC). Basic principle of the SC is to measure the input power and then iteratively search for a flux level until the minimum of input power is detected, while the output power of motor is constant [1]. The main drawbacks of search controller are slow convergence and high torque ripple. The LMC method computes the losses by using machine model and selects a flux level that minimizes the losses, it has a fast response and produces small torque ripple [2-5]. In [2], the minimum loss control algorithm is suggested without considering the core loss. Hence, the result of minimum loss model is not accomplished perfectly. In [3], the loss minimization model uses a simplified IM equivalent circuit which neglects the leakage inductance. The similar model of loss minimization is developed without sacrificing the leakage inductance, and a different optimal flux level from the one in [3] is suggested in [4]. However, the complicated approach makes that expression difficult to be realized for the generalized model for the different types of motors. In [5], the development of a closed-form equation, that is similar to the one in [3], is suggested without neglecting leakage inductances. But it has to find the loss expression from the full loss model which is very complex.

In this paper, a proposed LMC algorithm using the field oriented control (FOC) method is presented. The proposed LMC algorithm is very simple and based on a simplified equivalent circuit of the IM. The optimal flux level is obtained by the synchronous speed and the motor torque. The feasibility and effectiveness of the proposed LMC algorithm are supported by simulation and experimental results.

2. Induction Motor Model

Induction motor model in the rotor flux reference frame (λ_{qr}=0), assuming a constant stator angular frequency ω_s, is given by the following equations.

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\lambda_{qs} + \omega_s \lambda_{ds} \tag{1}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \omega_s \lambda_{qs} \tag{2}$$

$$0 = R_r i_{qr} + \frac{d}{dt}\lambda_{qr} + (\omega_s - \omega_r)\lambda_{dr} \tag{3}$$

$$0 = R_r i_{dr} + \frac{d}{dt}\lambda_{dr} - (\omega_s - \omega_r)\lambda_{qr} \tag{4}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \tag{5}$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \tag{6}$$

$$0 = L_r i_{qr} + L_m i_{qs} \tag{7}$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \tag{8}$$

The electromagnetic torque can be derived:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}) = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_{dr} i_{qs} \tag{9}$$

Note that the torque is proportional to the product of the rotor flux linkage and the stator q-axis current.

3. Loss Minimization Control Algorithm

The motor losses are calculated from the IM equivalent circuit in Fig. 1. In the steady state of the IM model, there is no leakage inductance on the rotor side. Using the IM steady-state rotor flux oriented model in which the iron loss resistance is included and shown in Fig. 2.

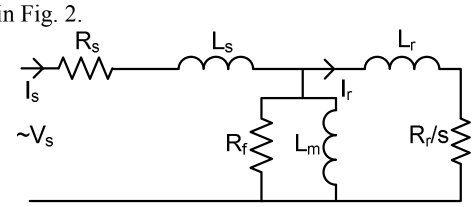


Fig.1. IM equivalent circuit used to model the losses.

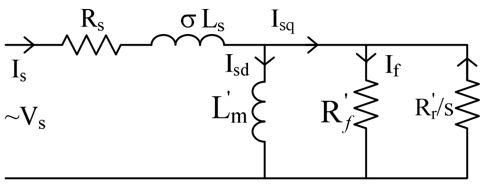


Fig.2. IM steady state equivalent circuit in the RFO frame

The motor total losses can be expressed:

$$P_{total} = P_{cus} + P_{cur} + P_{iron}$$

$$= R_s(i_{ds}^2 + i_{qs}^2) + R_r^{'}(i_{dr}^2 + i_{qr}^2) + \frac{1}{R_f^{'}}(\omega_s L_m^{'})^2 i_{ds}^2 \quad (10)$$

where P_{cus} is stator copper losses, P_{cur} is rotor copper losses and P_{iron} is iron losses.
The rotor currents in terms of the stator currents are derived from equations (7) and (8):

$$i_{qr} = -\frac{L_m}{L_r} i_{qs} \quad (11)$$

$$i_{dr} = 0 \quad (12)$$

Substituting (11)-(12) into (10) the total losses can be expressed:

$$P_{total} = R_s i_{ds}^2 + R_s i_{qs}^2 + R_r^{'} i_{qs}^2 + \frac{1}{R_f^{'}}(\omega_s L_m^{'})^2 i_{ds}^2 \quad (13)$$

Rearranging (13) the following losses are obtained:

$$P_{total} = (R_s + \frac{1}{R_f^{'}}(\omega_s L_m^{'})^2) i_{ds}^2 + (R_s + R_r^{'}) i_{qs}^2$$

where

$$R_d = R_s + \frac{1}{R_f^{'}}(\omega_s L_m^{'})^2 \quad R_q = R_s + R_r^{'}$$

Total losses can be expressed:

$$P_{total} = R_d i_{ds}^2 + R_q i_{qs}^2 \quad (14)$$

In the field oriented control, the stator and rotor currents can be given in terms of T_e and λ_{dr} in the steady state:

$$i_{qs} = \frac{4}{3p}\frac{L_r}{L_m}\frac{T_e}{\lambda_{dr}} \quad (15)$$

$$i_{ds} = \frac{\lambda_{dr}}{L_m} \quad (16)$$

Substituting (15), (16) into (14), the total loss P_{total} is described by function of T_e and λ_{dr}:

$$P_{total} = R_d \frac{\lambda_{dr}^2}{L_m^2} + R_q \frac{16}{9p^2}\frac{L_r^2}{L_m^2}\frac{T_e^2}{\lambda_{dr}^2} \quad (17)$$

The minimum loss can be obtained when the differentiation of P_{total} with respect to λ_{dr} is equal to zero. Then, differentiation of P_{total} results:

$$\frac{dP_{total}}{d\lambda_{dr}} = 2\frac{R_d}{L_m^2}\lambda_{dr} - 32\frac{R_q}{9p^2}\frac{L_r^2}{L_m^2}\frac{T_e^2}{\lambda_{dr}^3} = 0 \quad (18)$$

The solution of (18) is given by

$$\frac{\lambda_{dr}^2}{L_m^2} = \frac{R_q}{R_d} i_{qs}^2 \quad (19)$$

The equation of (19) is expressed as following equation (20). The optimal flux component for minimum loss is given by

$$i_{op\_ds}^{*} = \sqrt{\frac{R_q}{R_d(\omega_s)}} i_{qs} \quad (20)$$

Based on the above LMC algorithm, the block diagram of the indirect FOC method for IM drive is shown in Fig.3.

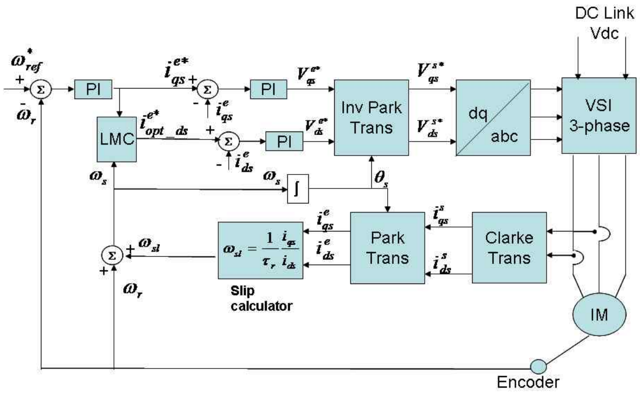


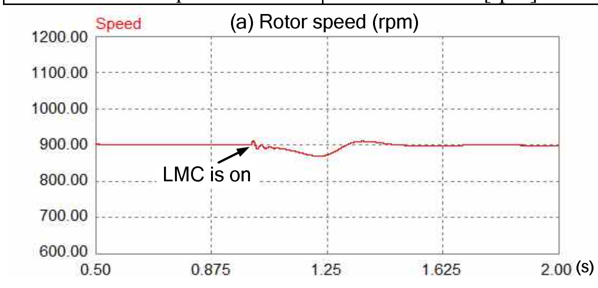
Fig.3. The block diagram of proposed LMC based on indirect FOC method

4. Simulation results

In order to verify the proposed LMC algorithm, simulation is carried out by PSIM6.0 software. A 2.2kW IM is examined by the FOC method at load torque 1.2Nm. The IM parameters are given in Table 1.
Fig. 4 shows the speed, torque and stator currents responses before and after applying the LMC algorithm. The IM is running at reference speed 900 rpm and load torque 1.2 Nm. The LMC algorithm is activated at t = 1s. When LMC is applied, a slight dip in speed is observed but the speed recovery to the command speed is very fast and within 0.5s in Fig. 4a, and the responded time is dependent on PI gains design. Furthermore, the currents, i_{ds} and i_{qs}, are readjusted by the FOC method to achieve the minimum loss and the motor torque is maintained constant as same as the load torque 1.2Nm. The total power loss is decreased significantly to the minimum value shown in Fig. 4f. Accordingly, the three-phase stator currents are smaller shown in Fig. 4g. Furthermore, with the optimal flux level obtained from the LMC algorithm, the torque ripple is reduced greatly in Fig. 4d.
Fig. 5 shows the total loss summary of IM controlled by the FOC method using the with/without proposed LMC algorithm at constant load torque 1.2 Nm and various speed levels. The optimal total losses are always smaller than that obtained from the conventional FOC method without using the LMC algorithm.

Table1 Induction motor parameters

Parameters	Value
Rated power	3 [HP]
Rated voltage	220/380 [V], 60 [Hz]
Number of poles	4
Stator resistance	2.077 [Ω]
Rotor resistance	1.964 [Ω]
Iron loss resistance	686.53 [Ω]
Stator leakage inductance	0.026 [H]
Rotor leakage inductance	0.026 [H]
Mutual inductance	0.239 [H]
Rated speed	1720 [rpm]



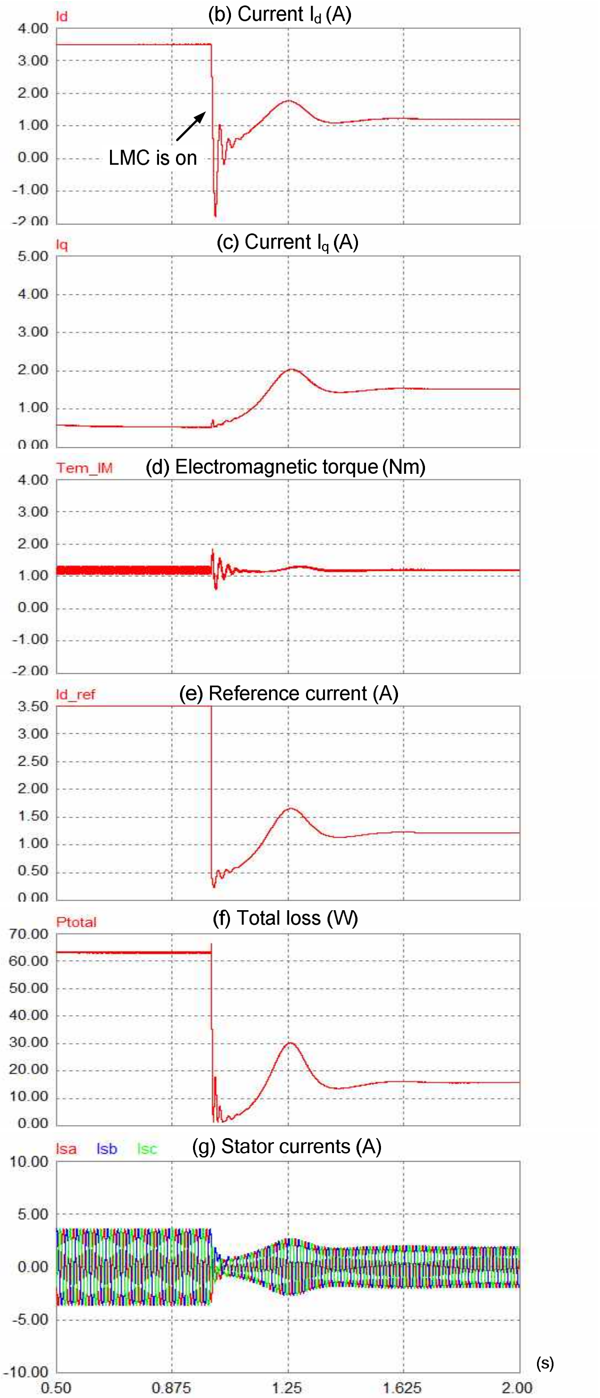


Fig. 4. Operation of IM using FOC method at rotor speed 900 rpm and load torque 1.2 Nm. The LMC algorithm is applied at 1s.

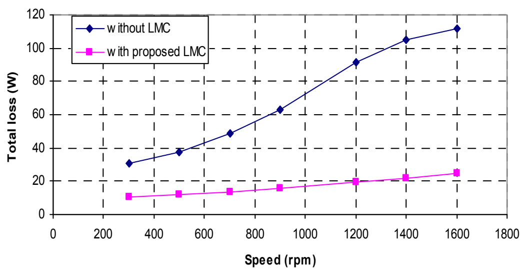


Fig. 5 Comparison of total loss with and without proposed LMC algorithm

5. Experimental results

The proposed LMC algorithm is verified experimentally with the Ti DSP TMS320LF2406A. The hardware setup consists of 2.2kW IM which has parameters given in Table 1 and a 2.2 kW DC generator acted as a load, shown in Fig. 6.

Fig. 7 shows the operation of 2.2kW IM at the speed and load conditions as same as the simulation, 900rpm and 1.2Nm (10% rated torque). The experimental results almost match the simulation results. The minimum total loss is achieved as the LMC algorithm is turned on and the smaller torque ripple is also benefited from the LMC algorithm.

Fig. 8 shows the experimental results of total loss at constant load torque and various speed levels. The proposed LMC algorithm always gives the smaller power loss compared to the conventional FOC method.

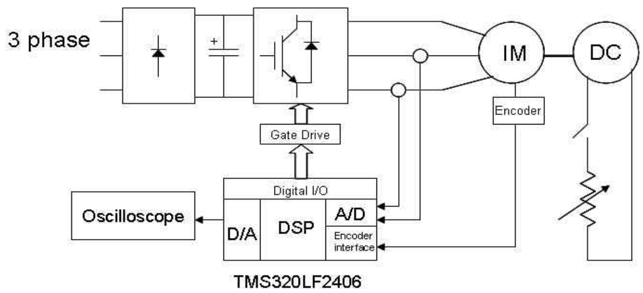
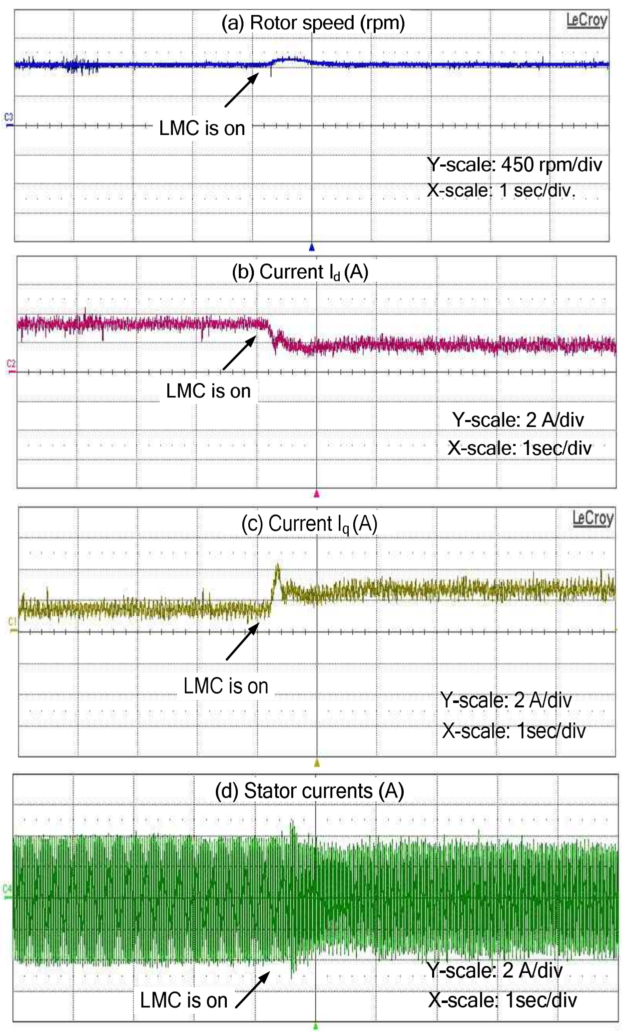
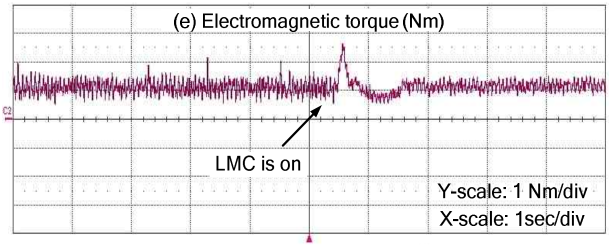


Fig. 6. Block diagram of experimental implementation





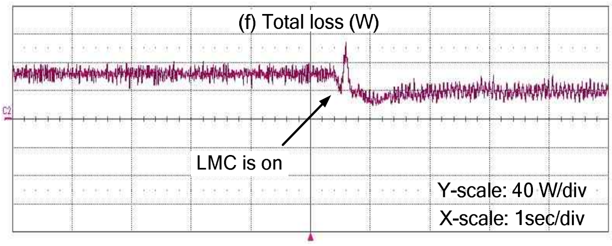


Fig. 7. Experimental results of the IM drive with and without the proposed LMC algorithm when motor operates at 900 rpm with 10 % of rated torque.

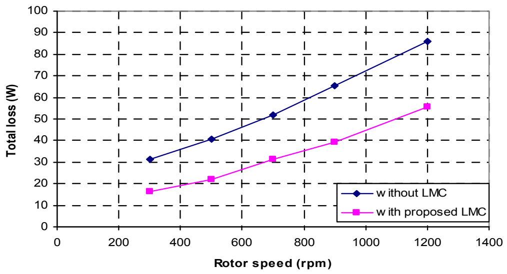


Fig. 8. Experimental results of total losses with and without proposed LMC algorithm

6. Conclusion

A new loss minimization controller for IM drive was presented in this paper. The proposed LMC based on the simplified equivalent circuit and simplified model. The performance of the proposed controller was tested in both simulation and experimental conditions. From the results the proposed LMC was advantaged in terms of power saving and torque ripple minimization as compared those without the LMC. The validity and effectiveness of the proposed control method was significantly verified by simulation and experimental results.

Reference

[1] F.Abrahamsen, F.Blaabjerg, J.Pedersen, P.Grabowski, P.Thogersen, "On the energy optimized control of standard and high-efficiency induction motors in CT and HVAC applications", IEEE Trans. on Ind. App., 1998, vol.4, pp:822 831.

[2] Jae Ho Chang, Byung Kook Kim, "Minimum-time minimum-loss speed control of induction motors under field-oriented control", IEEE Trans. Ind. Electron., vol. 44, no. 6, pp. 809-815, Dec. 1997

[3] G. O. Garcia, J. C. Mendes Luis, R. M. Stephan, and E. H. Watanabe, "An efficient controller for an adjustable speed induction motor drive," IEEE Trans. Ind. Electron., vol. 41, no. 5, pp. 535–539, Oct. 1994.

[4] S. Lim and K. Nam, "Loss-minimising control scheme for induction motors," Proc. Inst. Elect. Eng., vol. 151, no. 4, pp. 385–397, Jul. 2004.

[5] M. N. Uddin, S. W. Nam, "New online loss-minimization-based control of an induction motor drive", IEEE Trans. Power Electronics, Vol. 23, No. 2, pp 926-933, Mar. 2008

Appendix

Nomenclature

R_s, R_r Resistance of a stator and rotor phase winding.

L_s, L_r Self inductance of the stator and the rotor.

L_m Magnetizing inductance.

σ Leakage factor $(1 - L_m^2/(L_s L_r))$.

$R_r^{'}$ Referred rotor resistance $R_r^{'} = (L_m/L_r)^2 R_r$.

$L_m^{'}$ Referred magnetizing inductance $(L_m^{'} = (1-\sigma)L_s)$.

ω_s Stator angular speed.