Novel Loss Optimization in Induction Machines with Optimum Rotor Flux Control

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Abstract—This paper focus on seeking optimum rotor flux which optimizes total energy control under practical constraints of currents, voltages and speed measurements. Improved flux optimization method is an important criteria to evaluate losses in indirect field oriented control for induction machine drives. The practical usefulness of our control models are evaluated and confirmed through experiments using an induction machine (1.5kW/380V). Simulation and experimental investigation tests are provided to evaluate the consistency and performance of the proposed control model.

Keywords: Induction Machines, Loss Optimization, Optimum Flux, Field Oriented Control.

NOMENCLATURE

u_{sd} , u_{sq} : dq-axis equivalent stator voltages

i_{sd} , i_{sq} : dq-axis equivalent stator currents

i_{rd} , i_{rq} : dq-axis equivalent rotor currents

ϕ_{sd} , ϕ_{sq} : dq-axis equivalent stator fluxes

ϕ_{rd} , ϕ_{rq} : dq-axis equivalent rotor fluxes

r_s , r_r : Stator and rotor resistances

ω_s , ω : Synchronous and mechanical speeds

$\omega_{sl} = \omega_s - \omega$: The slip angular speed

l_m , l_s , l_r : Mutual, stator and rotor inductances

p : Number of pole pairs

J : Inertia constant of the machine

m_M , m_L : Motor and load torques

k : Viscous friction coefficient of machine and load.

r_c : Iron loss resistance

σ : Leakage coefficient of the machine

$\tau_r = \dfrac{l_r}{r_r}$: Rotor time constant

1. INTRODUCTION

Induction machines are extensively used in industrial applications due to their high performance, efficiency, and simple control characteristics. They are also attractive in new electric generation ships, water pumps, electric transportation systems (Abrahamsen, F., Blåbjer, F., J.K. Pederson, J.K. (1997); Faiz, J., Sharifian, M.B.B. (2006). These applications require different power levels ranging from a few to several hundred horsepower. There are general purpose loss minimization techniques which approaches are different depending on the induction machine drives applications. Clearly, by using the advances in power electronics and signal processing (DSP) technologies, the control schemes of induction machines have been improved from simple scalar or auto-tuning control to field oriented and direct torque controls (Abourida, S., Belanger, J. (2009); Bazzi, A.M., Krein, P.T.(2009); El-Refaei, A., Mahmoud, S., Kennel, R. (2005); Krause, P.C., Wasynczuk, O., Sudhoff, S.D. (1986); Siva Reddy, Y.V., Vijayakumar, M., Brahmananda Reddy, T. (2007); Vas, P. (1990)). The field oriented control is successfully applied in real time control of industrial applications when dealing with high performance induction machines drives (Bezanella, A. S., R. Reginetto, R. (2001); Holtz, J. (2006); Inanc, N. (2007); Novotny, D.W., Lipo, T.A. (1996); Singh, G.K. (2005); Wang, B., Chiasson & Bodson,

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M. and Tolbert, L.M. (2007)).

Field oriented control implementation can achieve robust control performance in induction machines. Estimating the magnitude and phase of rotor flux is the key of the control implementation (Abrahamsen, F., Blåbjer, F., J.K. Pederson, J.K. (1997); Camblong, H., Martinez de Alegria, I., Rodriguez, M., Abad, G. (2006); Jemli, M., Boussak, M., Gossa, M., Kamoun, M. B. A. (2000)). Direct methods in sensing the rotor flux by using suitable hardware around the machine have proved to be inaccurate and impractical at speed and torque variations (Geng, Y., Hua, G., Huangang, W. and Pengyi, G. (2004)). Indirect methods of sensing the rotor flux employ a mathematical model of induction machine by measuring state variables of currents, voltages and rotor position. The accuracy of this method depends mainly on accuracy of time rotor constant variation (Chang, G. W., J. P. Hespanha, Morse, A. S., Netto, M. S., Ortega, R. (2001); Grouni, S., Ibtiouen, R., Kidouche and M., Touhami O. (2008); Marino, R., Tomei, P., Verrelli, C. M. (2008); Wang, B., Chiasson & Bodson, M. and Tolbert, L.M. (2007)). The machine parameters may change during operation which introduces inaccuracies in the estimated flux (Bezanella, A. S., R. Reginetto, R. (2001)).

With an aim to improve performance of systems control of induction machine, research has been conducted to design advanced nonlinear controllers (Dhaoui, M., Sbita, L. (2010); Faiz, J., Sharifian, M.B.B. (2006); Holtz, J. (2006)). Most of these controls operate at constant flux norms (Levi, E. (1995); Krishnan, R. (2001)). In this situation, efficiency is maximized only when the system operates at its nominal torque (Ren, J.Q., Ii, Y.H., Xu, W., Wang, K. (2008); Ta, C. M., Hori, Y. (2001)). Away from this operating point the machine will dissipate a considerable part of the injected electrical power as core losses and it may inefficiently store too much energy in its coil inductances (Abrahamsen, F., Blåbjer, F., J.K. Pederson, J.K. (1997); Thanga Raj, C., Srivastava, S.P., Agarwal, P. (2009)). However, in most applications, induction machines do not operate at the nominal rate since the desired torque may change on-line or may depend on system states such as position or velocity. It is then technically and economically interesting to investigate other modes of flux operation seeking to optimize system performance (Bazzi, A.M., Krein, P.T. (2009)). Aware of these facts, some previous works have already used the reference flux as an additional parameter seeking to increase machine efficiency or to maximize the delivered torque in minimum time (Bezanella, A. S., R. Reginetto, R. (2001); Camblong, H., Martinez de Alegria, I., Rodriguez, M., Abad, G. (2006); Geng, Y., Hua, G., Huangang, W. and Pengyi, G. (2004); Inanc, N. (2007)).

In this paper, a new loss optimization method is suggested to obtain an optimum rotor flux control for induction machine drives using indirect field oriented control with practical constraints of currents, voltages and position measurements. Implementation of indirect field oriented control is effective for induction machine drives based on flux optimization method. The practical usefulness of our control models are evaluated and confirmed through experiments using an induction machine (1.5kW/380V). Simulation studies and experimental investigation tests show the performance of the proposed control model.

2. INDUCTION MACHINE MODEL AND CONTROL FORMULATION

In this section, the dynamic mathematical model of induction machine is available in literature (Krause, P.C. et al. (1986); Krishnan, R. (2001); Novotny, D.W., Lipo, T.A. (1996); Vas, P. (1990)). Parasitic effects such as hysteresis, eddy currents and magnetic saturation are neglected. The state-space model of system equations related to indirect field oriented control method is described below. The three phase voltages of machine drives in reference frame with synchronously rotating speed ω_s are described by the following equations (Krause, P.C., Wasynczuk, O., Sudhoff, S.D. (1986)):

$$u_{sd} = r_s i_{sd} + \frac{d\phi_{sd}}{dt} + \omega_s \phi_{sq} \tag{1}$$

$$u_{sq} = r_s i_{sq} + \frac{d\phi_{sq}}{dt} + \omega_s \phi_{sd} \tag{2}$$

$$0 = r_r i_{rd} + \frac{d\phi_{rd}}{dt} + \omega_{sl} \phi_{rq} \tag{3}$$

$$0 = r_r i_{rq} + \frac{d\phi_{rq}}{dt} + \omega_{sl} \phi_{rd} \tag{4}$$

The motor or electromagnetic torque and mechanical speed of induction machine can be expressed:

$$m_M = p \frac{l_m}{l_r} (\phi_{rd} i_{sq} - \phi_{rq} i_{sd}) \tag{5}$$

$$\frac{d\omega}{dt} = \frac{1}{J} (m_M - m_L - k\omega) \tag{6}$$

where the speed $p\Omega = \omega$

In vector controlled system, rotor flux vector has only the real component, which is constant in steady state (Holtz, J. (2006); Krishnan, R. (2001); Novotny, D.W., Lipo, T.A. (1996); Vas, P. (1990)). The rotor currents are written as fallows:

$$i_{rd} = \frac{1}{l_r} (\phi_{rd} - l_m i_{sd}) \tag{7}$$

$$i_{rq} = \frac{1}{l_r} (\phi_{rq} - l_m i_{sq}) \tag{8}$$

Substituting (7), (8) into (3) and (4), yields two expressions of dynamic rotor flux components:

$$\frac{d\phi_{rd}}{dt} + \frac{1}{\tau_r} \phi_{rd} - \frac{l_m}{\tau_r} i_{sd} - \omega_{sl} \phi_{rq} = 0 \tag{9}$$

$$\frac{d\phi_{rq}}{dt}+\frac{1}{\tau_r}\phi_{rq}-\frac{l_m}{\tau_r}i_{sq}+\omega_{sl}\phi_{rd}=0 \qquad (10)$$

Electromagnetic or motor torque is controlled only by q-axis stator current. With $\phi_{rq}=0$, $i_{rd}=0$, it yields:

$$\frac{d\phi_{rd}}{dt}=\frac{d\phi_{rq}}{dt}=0 \qquad (11)$$

$$m_M=p\frac{l_m}{l_r}\phi_{rd}i_{sq} \qquad (12)$$

The equations (7) and (8) become:

$$i_{rq}=-\frac{l_m}{l_r}i_{sq} \qquad (13)$$

$$\phi_{dr}=\phi_r=l_m i_{ds} \qquad (14)$$

$$\omega_{sl}=\frac{l_m}{\tau_r}\frac{i_{sq}}{\phi_{rd}}=\frac{1}{\tau_r}\frac{i_{sq}}{i_{sd}} \qquad (15)$$

Combining equations (9), (10) and (15), the following references are obtained:

$$i_{sd}^*=\frac{1}{l_m}(\tau_r\frac{d\phi_r^*}{dt}+\phi_r^*) \qquad (16)$$

$$i_{sq}^*=\frac{l_r}{pl_m}\frac{m_M^*}{\phi_r^*} \qquad (17)$$

$$\omega_{sl}^*=\frac{l_m}{\tau_r}\frac{i_{sq}^*}{\phi_r^*} \qquad (18)$$

3. POWER LOSSES ANALYSIS IN CONTROLLED VECTOR INDUCTION MACHINE

Power losses in controlled vector induction machine drives, including electrical, magnetically losses and mechanical losses may be computed and founded (Bernal, F.F., Cerrada, A.G., Faure, R. (2000)). The expression of electromagnetic total power expressed in the rotating (d,q) reference frame is quoted in many previously published papers (Bernal, F.F., Cerrada et al. (2000); Leidhold, R., Garcia, G., Valla, M.I. (2002)) and can be given by:

$$\begin{aligned}P_e&=\sigma l_s\left(i_{sd}\frac{di_{sd}}{dt}+i_{sq}\frac{di_{sq}}{dt}\right)-\frac{1}{l_r}\left(\frac{d\phi_{rd}}{dt}\phi_{rd}+\frac{d\phi_{rq}}{dt}\phi_{rq}\right)\\&+r_s\left(i_{sd}^2+i_{sq}^2\right)-r_r\left(i_{rd}^2+i_{rq}^2\right)+\frac{l_m}{l_r}\omega\left(\phi_{rd}i_{sq}-\phi_{rq}i_{sd}\right)\\&-\frac{2r_rl_m}{l_r}\left(i_{rq}i_{sq}+i_{rd}i_{sd}\right)\end{aligned} \qquad (19)$$

The total electrical power loss is written as:

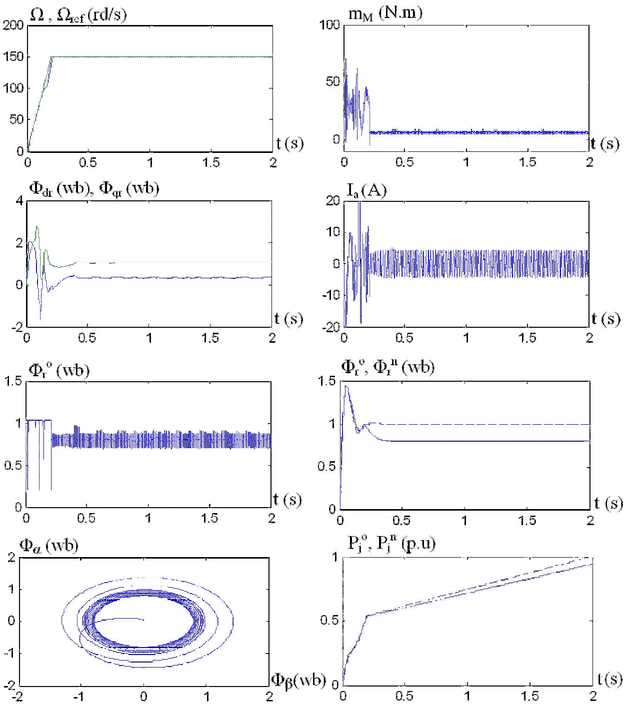

Fig.1. Simulation results of the rotor flux control variation in indirect field oriented control of induction machine

$$\Delta P_{1e}=\left(r_s+\frac{r_rl_m^2}{l_r^2}\right)\left(i_{sd}^2+i_{sq}^2\right)+\left(\frac{r_rl_m^2}{l_r^2}+r_c\right)\left(\frac{\phi_r}{l_m}\right)^2 \qquad (20)$$
$$-\frac{r_rl_m}{l_r^2}i_{sd}\phi_r$$

The solution of optimization problem can easily show that optimal flux depends only of differential flux function (Abrahamsen, F., Blåbjer, F., J.K. Pederson, J.K. (1997); Bazzi, A.M., Krein, P.T. (2009); Grouni, S., Ibtiouen, R., Kidouche and M., Touhami O. (2010)). The objective function of optimization is given by solving:

$$J=\int_0^T f(m_M^*(t),\phi_r(t),\frac{d\phi_r}{dt})dt,\ \forall T\in[0,T] \qquad (21)$$

The optimum flux function is given by:

$$\phi_r=f(m_M) \qquad (22)$$

Optimum operation point, corresponding to minimum loss is obtained by differentiating (22):

$$\phi_r^{opt}=\beta\sqrt{|m_M|} \qquad (23)$$

where:

$$\beta=\left(\frac{l_r^2r_s+r_rl_m^2}{(r_s+r_c)p^2}\right)^{1/4} \qquad (24)$$

The optimal control is then found to be:

$$u_1^o = \frac{\tau_r}{l_m}\left(\frac{d\phi_r^{opt}}{dt} + \frac{1}{\tau_r}\phi_r^{opt}\right) \tag{25}$$

To validate the proposed optimization control, some numerical results of simulation are shown:

In Fig.1, the behavior of the drive is shown under low load and speed conditions. It shows numerical results in field oriented control of respectively the nominal and optimum fluxes operating in both transient and steady state. The speed and torque follows their references. The graph shows successfully flux decoupling. Imposing an optimum flux reference we have obtained an improvement control loss optimization and have plotted the circular locus of fluxes. The stator current waveform has shown a fast rise time response.

3.1 Loss optimization modeling function $i_{sd} = f(i_{sq})$

The loss optimization is given by using the objective function linking two components of stator current for a copper loss minimization. The expression of power losses is given by (Grouni, S., Ibtiouen, R., Kidouche, M., Touhami, O. (2010):

$$\Delta P_t = \sigma l_s\left(i_{sd}\frac{di_{sd}}{dt} + i_{sq}\frac{di_{sq}}{dt}\right) - \frac{l_m}{\tau_r l_r}\phi_{rd} i_{sd} + \left(r_s + \frac{l_m^2}{l_r \tau_r}\right)\left(i_{sd}^2 + i_{sq}^2\right) \tag{26}$$

In steady state, the stator current expression at minimum power loss is:

$$i_{sd} = \left(1 + \frac{l_m^2}{r_s l_r \tau_r}\right)^{\frac{1}{2}} i_{sq} \tag{27}$$

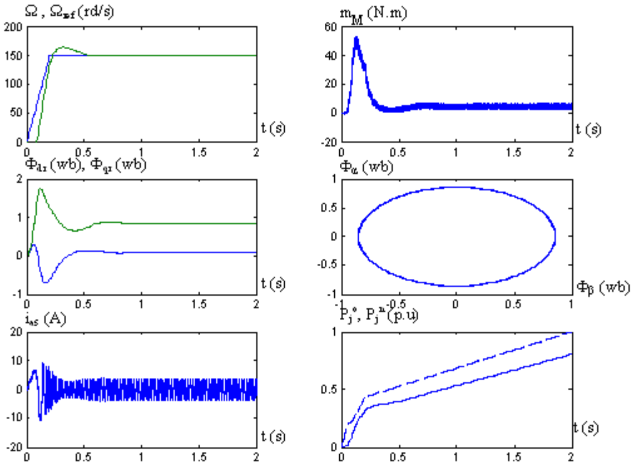

Fig.2. Simulation results of nominal and optimum rotor flux variation control

In Fig.2, numerical results are presented under load application 5 N.m with optimum flux. In order, to confirm the proposed control, we are taking into account deviations of motor parameters. The adaptation on line of rotor resistance is applied which reflects the losses in drives operation. The control of flux is successfully obtained between the decoupling flux and electromagnetic torque; q axis flux is maintained null and d-axis flux is constant. The speed and torque responses are presented in both transient and steady state. The variation curves of power loss have shown a reduced copper loss.

The importance of our control is that we took into account core loss during optimization process. In the steady state, this approach method gives a good performance and the implementation becomes more effective. The comparison between loss optimization in Fig.1 and Fig.2 shows the improved response with iron and core losses parameters variations.

3.2 Loss optimization modeling function $i_{sd} = f(i_{sq}, \omega)$

Loss optimization is presented by introducing the mechanical phenomena (Kioskeridis, I., Margaris, N. (1996); Levi, E. (1995); Ren, J.Q., Ii., Y.H., Xu, W., Wang, K. (2008)). Copper and iron losses are:

$$\Delta P_v = r_s\left(i_{sd}^2 + i_{sq}^2\right) + \frac{r_r r_c}{r_r + r_c} i_{sq}^2 - \frac{l_m^2\omega^2}{r_r + r_c} i_{sd}^2 \tag{28}$$

The expression of stator current that gives the minimum loss at the steady state is given by:

$$i_{sd} = \sqrt{\frac{r_s r_r + r_s r_c + r_r r_c}{l_m^2\omega^2 - r_s(r_r + r_c)}}\, i_{sq} \tag{29}$$

The simulation results in Fig.3 show a fast time fluxes response. The analysis of dynamic speed response in steady state follows perfectly the reference speed but the speed rise time became slow because of the physical mechanical friction. It shows a good response of stator current. We can also be noticed that even by including the mechanical friction were still reduce losses.

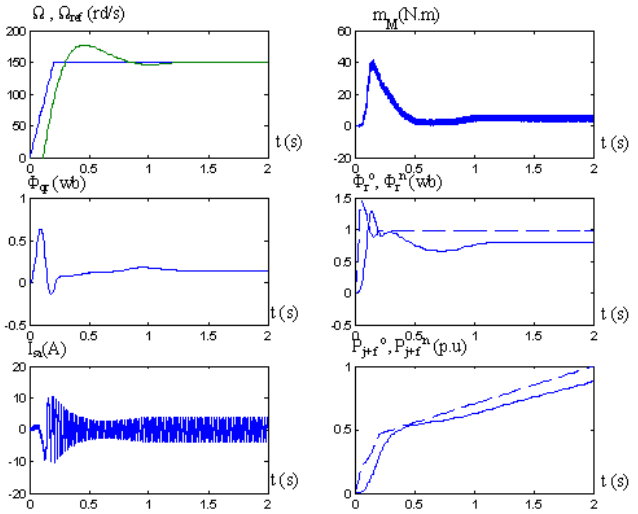

Fig.3. Simulated results of speed and torque control including mechanical phenomena and considering iron loss

The parameters r_c, r_s and r_r changes with temperature and the implementation are effective for load control.

The proposed system control drives will be validated by using experiments set-up.

5 EXPERIMENTAL RESULTS

The proposed drive set-up is implemented with a 1.5 kW induction machine. It has been used to clarify the practical operation and performance of the optimization control. However, to validate the control of power losses in steady state, the measured tests are obtained with a 5 N.m external load.

Fig.4 shows the measured responses of speed and torque control under 5 N.m variation load. The response of speed changes from zero to 1225 rpm at the time 0.2 s. Although the parameters are varied to a significant extent, the transient responses remain much closed together. The proposed drive system therefore has a good robustness. The measured torque response behavior in transient and steady state regime is obtained. In Fig.5, the measured response of total power loss minimization is obtained at optimum flux control variation in steady state conditions. This response presents a satisfactory of control variation. In Fig.6, the measured response of total power losses is obtained at rotor flux control variation.

The experimental results obtained demonstrate a good dynamic of the drive for both transient and steady state.

Again, the comparison of these responses presented in Fig.5 and Fig.6 of total power loss optimization are improved for low load.

4. CONCLUSION

We have presented in this paper a new loss optimization method in controlled vector induction machine with optimum rotor flux control taking into account parameters variation. It has been implemented in practical real time. This method has successfully demonstrated the control drive with optimum rotor flux control using only the stator currents, voltages and velocity measurements. Experimental and simulation results are presented. It is noted that the proposed method achieves a good performance and minimizes the total power loss of induction machine drives.

To get in depth in this area, one can analyze pulse width modulation PWM signals quantification and optimize efficiency.

APPENDIX

The induction machine used for test is 380/220V three-phase, 50 Hz, 1.5 kW, 3.64A(Y) 6.31A(Δ), four-pole, 1420 r/min, motor with the following parameters in the per phase steady state equivalent circuit:

r_s= 4.85Ω, r_r= 3.805Ω, l_s= 274 mH, l_r= 274 mH, l_m= 258 mH, J= 0.031 kg.m^2, k= 0.008 Nm.s/rd.

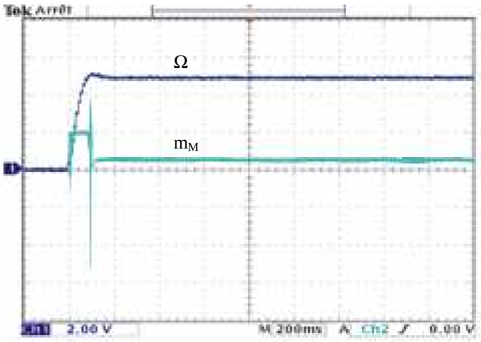

Fig.4. Experimental responses of speed and electromagnetic torque control. Scale: Time t(s) 0.2 s/div. Speed (rpm) 500 rpm/div and Torque (N.m) 5 N.m/div

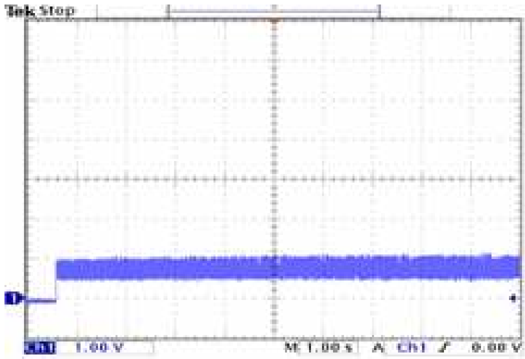

Fig.5. Experimental steady state response of loss optimization with optimum rotor flux control. Scale: Time t(s) 1s/div and power loss 500W/div

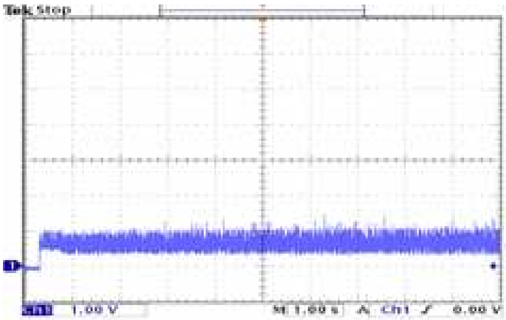

Fig.6. Experimental steady state response of loss optimization with rotor flux control. Scale: Time t(s) 1s/div and power loss 500W/div

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