Application of Indirect Field Oriented Control with Optimum Flux for Induction Machines Drives

S. Grouni [1 2], R. Ibtiouen [2], M. Kidouche [1], O. Touhami [2]
[1] University of Boumerdes, Boumerdes, 35000 ALGERIA
[2] Polytechnics School, El harrach Algeria 16000 ALGERIA
E-mail: Said Grouni (**sgrouni@yahoo.fr**) Rachid Ibtiouen (**ribtiouen@yahoo.fr**)
E-mail: Madjid Kidouche (**kidouche_m@hotmail.com**) Omar Touhami(**omar.touhami@enp.edu.dz**)

Abstract— The rotor flux optimization is crucial parameter in the implementation of the field oriented control. In this paper, we considered the problem of finding optimum flux reference that minimizes the total energy control for induction machine drive under practical constraints: voltage and current. The practical usefulness of this method is evaluated and confirmed through experiments using (1.5kW/380V) induction machine. Simulations and experimental investigation tests are provided to evaluate the consistency and performance of the proposed control model scheme.

***Keywords*—** Indirect Field Oriented Control (IFOC), Induction Machine, Loss Optimization, Optimum Rotor Flux.

I. INTRODUCTION

Induction machines are widely used in various industries as prime workhorses to produce rotational motions and forces. Generally, variable speed drives for induction machines require both wide speed operating range and fast torque response, regardless of load variations. These characteristics make them attractive for use in new generation electrical transportation systems, such as cars and trains. They are also used in ventilation and heating systems and in many other electrical domestic apparatus [8].

By using the advances of power electronics, microprocessors, and digital signal processing (DSP) technologies, the control schemes of induction machines changed from simple scalar or auto-tuning to Field Oriented Control "FOC" and Direct Torque Control "DTC". The FOC is successfully applied in industrials applications on real time control when dealing with high performance induction machines drives [1], [2], [9], [10], [11].

The FOC is the most suitable way in achieving a high performance control for induction machines. Estimating the magnitude and phase of rotor flux is very crucial for the implementation control field oriented method. Direct ways of sensing the rotor flux by implementing suitable hardware around the machine have proved to be inaccurate and impractical at speed and torque. Indirect methods of sensing the rotor flux employ a mathematical model of induction machine by measuring state variables, like currents and voltages. The accuracy of this method will depend mainly on the precise knowledge time constant. This of rotor machine parameter may change during the operation of the drive, which introduce inaccuracies in the flux estimation as both stator and rotor resistance windings change with temperature [2], [7], [9].

With an aim to improve induction machines performance and stability properties, researches have been conducted to design advanced nonlinear control systems [4], [8], [13]. Most of these systems operate with constant flux norms fixed at nominal rate [8], [19].In this situation, maximum efficiency is obtained .However machines do not operate at their nominal rate as the desired torque changes 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. Aware of these facts, some previous works have already used the reference flux as an additional degree of freedom to increase machine efficiency [6], [9].

This problem has been treated by many researchers. In [13], [18], [20], the heuristics approaches used offer fairly conservative results. They are based on measurement of supplied power in approximating the optimum flux algorithm. The convergences of these algorithms are not guaranteed.

In [17], an applied analytical approach has been used directly in real time to obtain the optimal trajectory equation of the control drives, nevertheless this solution is less robust than the heuristics methods.

In this paper, the objective of the newly developed method is to offer a unified procedure by adding the adaptation parameters and reducing losses. Our work will be structured as follows: In section II, the induction machine model is first presented, then in Section III, we will describe the application of field oriented current and voltage vector control. In section IV, a new optimization approach of optimum flux is described and analyzed in both simulation and practical control. Finally, we have applied several techniques reducing losses with optimum rotor flux in indirect field oriented control for induction machine at variable speed. Simulation and practical results are given to demonstrate the advantages of the proposed scheme. Conclusion and further studies are explained in the last section.

K. Elleithy (ed.), *Advanced Techniques in Computing Sciences and Software Engineering*
DOI 10.1007/978-90-481-3660-5_2,

II. CONTROL PROBLEM FORMULATION

A. Dynamic induction machine model

Mathematical model of induction machine in space vector notation, established in d-q axis coordinates reference rotating system at ω_s speed can be represented in the Park's transformation shown in Fig.1.

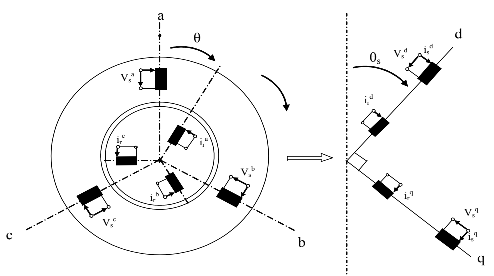

Fig.1. Scheme of Park transformation for induction machines

Standard dynamic model of induction machine are available in the literature. Parasitic effects such as hysteresis, eddy currents, magnetic saturation, and others are generally neglected. The state-space model of the system equations related to the indirect method of vector control is described below. The reference frame with the synchronously rotating speed of ω_s, d-q-axis voltage equations are [15].

$$v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \tag{1}$$

$$v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} \tag{2}$$

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

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

Where ω_s, ω are the synchronous and rotor angular speeds.

The stator and rotor fluxes are defined by the following magnetic equations:

$$\varphi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr} \tag{5}$$

$$\varphi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) = L_s i_{qs} + L_m i_{qr} \tag{6}$$

$$\varphi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) = L_r i_{dr} + L_m i_{ds} \tag{7}$$

$$\varphi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) = L_r i_{qr} + L_m i_{qs} \tag{8}$$

L_{ls}, L_{lr} and L_m are the stator leakage inductance, rotor leakage inductance, and mutual inductance, respectively.

The expressions of electromagnetic torque and mechanical speed are stated by:

$$C_{em} = p\frac{L_m}{L_r}(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}) \tag{9}$$

$$\frac{d\omega}{dt} = \frac{pL_m}{JL_r}(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}) - \frac{p}{J}C_r - \frac{f_r}{J}\omega \tag{10}$$

The difficulty of equation (9), is the strong coupling between flux and current of machine.

B. Indirect Field Oriented Control (IFOC)

For the rotor flux oriented control system, the rotor flux linkage vector has only the real component, which is assumed to be constant in the steady state. From (7) and (8), the rotor currents are given by:

$$i_{dr} = \frac{1}{L_r}(\varphi_{dr} - L_m i_{ds}) \tag{11}$$

$$i_{qr} = \frac{1}{L_r}(\varphi_{qr} - L_m i_{qs}) \tag{12}$$

Substituting (11) and (12) into (3) and (4), we can extract two expressions of dynamic d-q axis rotor flux components are expressed by:

$$\frac{d\varphi_{dr}}{dt} + \frac{R_r}{L_r}\varphi_{dr} - \frac{L_m}{L_r}R_r i_{ds} - \omega_{sl}\varphi_{qr} = 0 \tag{13}$$

$$\frac{d\varphi_{qr}}{dt} + \frac{R_r}{L_r}\varphi_{qr} - \frac{L_m}{L_r}R_r i_{qs} + \omega_{sl}\varphi_{dr} = 0 \tag{14}$$

$\omega_{sl} = \omega_s - \omega$ is the slip angular speed

If the vector control is fulfilled such that q-axis rotor flux can be zero, and d-axis rotor flux can be constant, the electromagnetic torque is controlled only by q-axis stator current, therefore from (9), with $\varphi_{qr} = 0$, $i_{dr} = 0$, yields

$$\frac{d\varphi_{dr}}{dt} = \frac{d\varphi_{qr}}{dt} = 0 \tag{15}$$

$$C_{em} = p\frac{L_m}{L_r}(\varphi_{dr} i_{qs}) \tag{16}$$

Substituting (15) into (3) and (11)-(14) yields

$$i_{qr} = -\frac{L_m}{L_r} i_{qs} \tag{17}$$

$$\varphi_{dr} = L_m i_{ds} \tag{18}$$

$$\omega_{sl} = \frac{L_m}{T_r}\frac{i_{qs}}{\varphi_{dr}} = \frac{1}{T_r}\frac{i_{qs}}{i_{ds}} \tag{19}$$

where $T_r = L_r / R_r$ is the time constant of rotor, $\omega = \dot{\theta}$ with θ is the position of the rotor and i_{ds}, i_{qs} are the direct and quadrant axis components stator currents, where φ_{dr}, φ_{qr} are the two–phase equivalent rotor flux linkages and the rotor speed ω is considered as state variable and the stator voltage $\boldsymbol{v_{ds}}$, $\boldsymbol{v_{qs}}$ as command variables.

We have shown in equation (9) that the electromagnetic torque expression in the dynamic regime, presents the coupling between stator current and rotor flux. The main objective of the vector control of induction machine is, as in direct current (DC) machines, to control independently the torque and the flux [4]. This can be realized by using d-q axis rotating reference frame synchronously with the rotor flux space vector. The d-axis is aligned with the rotor flux space vector. Under this condition we have; $\varphi_{dr} = \varphi_r$ and $\varphi_{qr} = 0$. In this case the electromagnetic torque of induction machine is given by equation (16). It is understood to adjust the flux while acting on the component i_{ds} of the stator current and adjust the torque while acting on the i_{qs} component. One has two variables of action then as in the case of a DC machine.

Combining equations (13), (15) and (16) we obtain the following d-q-axis stator currents:

$$i_{ds}^* = \frac{1}{L_m}\left(T_r \frac{d\varphi_r^*}{dt} + \varphi_r^*\right) \tag{20}$$

$$i_{qs}^* = \frac{L_r}{pL_m}\frac{C_{em}^*}{\varphi_r^*} \tag{21}$$

$$\omega_{sl}^* = \frac{L_m}{T_r}\frac{i_{qs}^*}{\varphi_r^*} \tag{22}$$

The torque C_{em}^* and flux φ_r^* are used as references control and the two stator currents i_{ds} , i_{qs} as inputs variables [13], [19].

Combining equations (21)-(22) we obtain the following expression of reference torque as a function of reference slip speed.

$$C_{em}^* = p\frac{\varphi_r^{*2}}{R_r}\omega_{sl}^* \tag{23}$$

with $\omega_s^* = \omega + \omega_{sl}^*$

The references voltages are given in steady state by:

$$v_{ds}^* = R_s i_{ds}^* - \omega_s^* \sigma L_s i_{qs}^* \tag{24}$$

$$v_{qs}^* = R_s i_{qs}^* + \omega_s^* \sigma L_s i_{ds}^* \tag{25}$$

where σ is the total leakage coefficient given by:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{26}$$

These equations are functions of some structural electric parameters of the induction machine (R_s, R_r, L_s, L_r, L_m) which are in reality approximate values.

The rotor flux amplitude is calculated by solving (19), and its spatial position is given by:

$$\theta_s = \int_0^t \left(\omega + \frac{L_m i_{qs}}{T_r \varphi_r}\right) dt \tag{27}$$

C. simulation Study of IFOC voltage and current Control

A simulation study was carried out to investigate the following models controls used on a closed loop IFOC system which depend on the loading conditions. The current and voltage control simulations of IFOC are given by Fig.2 and Fig.3.

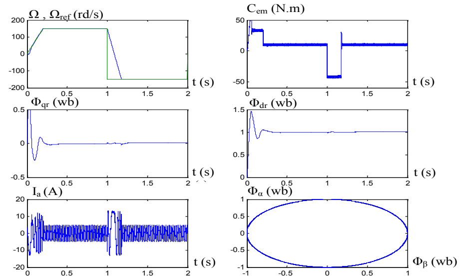

Fig. 2. Simulation of IFOC - IM drives with current control.

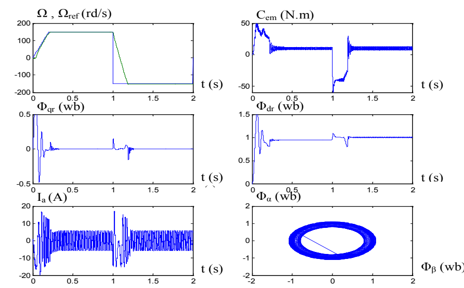

Fig. 3. Simulation of IFOC-IM drives with voltage control.

III. LOSS MINIMISATION IN IFOC INDUCTION MACHINE

A- Power losses of induction machine

In the majority constructions of induction machines, electromagnetic time constant is much smaller than mechanical time constant. For this reason the strategy of torque control which minimizes power losses can be reduced to the steady electromagnetic state. Several loss models are proposed and used in the literature, among this work those of [8], [9] and [10] which take into account the copper losses of the stator , the rotor windings and the iron losses. The total electrical input power of induction machine composed by resistive losses $P_{R,loss}$, power P_{field} stored as magnetic field energy in the windings and mechanical output power P_{mech} expressed in the d,q variables. Applying the transformation to rotating reference frame on d,q variables the total power is given by:

$$\begin{aligned} P_{el,total}(t) &= \sigma L_s\left(i_{ds}\frac{di_{ds}}{dt} + i_{qs}\frac{di_{qs}}{dt}\right) - \frac{1}{L_r}\left(\frac{d\varphi_{dr}}{dt}\varphi_{dr} + \frac{d\varphi_{qr}}{dt}\varphi_{qr}\right) \\ &+ R_s\left(i_{ds}^2 + i_{qs}^2\right) - R_r\left(i_{dr}^2 + i_{qr}^2\right) \\ &+ \frac{L_m}{L_r}\omega\left(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}\right) - \frac{2R_r L_m}{L_r}\left(i_{qr} i_{qs} + i_{qs} i_{ds}\right) \end{aligned} \tag{28}$$

This equation can be written in a condensed form as:

$$P_{el,total} = \frac{dP_{field}}{dt} + P_{R,loss} + P_{mech} \tag{29}$$

With:

$$P_{R,loss} = R_s\left(i_{ds}^2 + i_{qs}^2\right) + R_r\left(i_{dr}^2 + i_{qr}^2\right) \quad (30)$$

$$P_{field} = \sigma\frac{L_s}{2}\left(i_{ds}^2 + i_{qs}^2\right) + \frac{1}{2L_r}\left(\varphi_{dr}^2 + \varphi_{qr}^2\right) \quad (31)$$

$$P_m = \frac{L_m}{L_r}\omega\left(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}\right) \quad (32)$$

According to the equivalent diagrams, the model of iron losses is described by:

$$\Delta P_{Fe} = \Delta P_{Fe}^s = R_{Fe}\frac{\varphi_r^2}{L_m^2} \quad (33)$$

B. Power loss minimization with level flux control

B.1 Optimization flux for copper loss minimization

The flux optimization for minimized energy in steady state consists to find the optimal trajectory of flux, $\forall$ T $\in$[0,T], which minimizes the cost function. The optimum rotor flux calculation is given by the relation:

$$\varphi_r = f(C_{em}) \quad (34)$$

According to the dynamic model induction machine, the total electrical power loss can be written:

$$\Delta P_t = \left(R_s + \frac{R_r L_m^2}{L_r^2}\right)\left(i_{ds}^2 + i_{qs}^2\right) + \left(\frac{R_r L_m^2}{L_r^2} + R_f\right)\left(\frac{\varphi_r}{L_m}\right)^2 - 2\frac{R_r L_m}{L_r^2} i_{ds}\varphi_r = \beta_1\varphi_r^2 + \beta_2\frac{C_{em}^2}{\varphi_r^2} \quad (35)$$

Optimum operation point, corresponding to the minimum loss is obtaining by setting:

$$\frac{\partial(\Delta P_t)}{\partial\varphi_r} = 0 \quad (36)$$

The resolution of this equation, gives the optimum rotor flux:

$$\varphi_r^{opt} = \beta\sqrt{|C_{em}|} \quad (37)$$

Where

$$\beta = \left(\frac{L_r^2 R_s + R_r L_m^2}{\left(R_s + R_f\right)p^2}\right)^{1/4} \quad (38)$$

This parameter depends on machine operating.

From the equations (20) and (21) we deduce that the optimal control in the steady state is given by:

$$u_1^o = \frac{T_r}{L_m}\left(\frac{d\varphi_r^{opt}}{dt} + \frac{1}{T_r}\varphi_r^{opt}\right) \quad (39)$$

The optimization method consists in minimizing the copper losses in steady state while imposing the necessary torque defined by the speed regulator. To check the simulation results and to evaluate the feasibility and the quality of control, we carried out experimental test on the copper loss minimization by the flux variation method. It's noticed that the experimental result, Fig.6 is similar to the result found by simulation Fig.7.

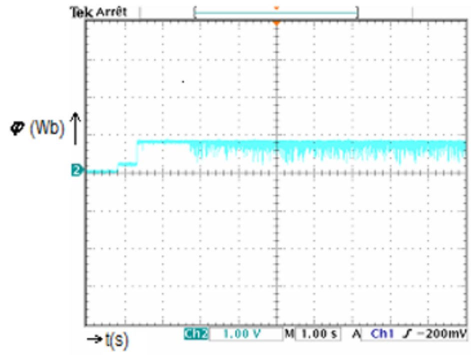

Fig.4. Experimental optimum flux variation

Fig.6 shows a simulation test, the curves of the losses in nominal and optimal mode with the application of a light load (C_r=5N.m), enable us to note that during load torque reduction, this method becomes more effective and it compensates excess loss by a flux reduction.

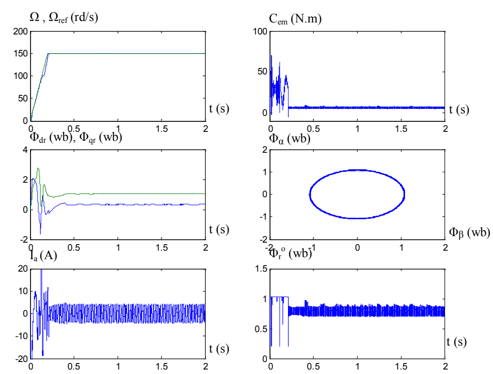

Fig.5. Simulation results of optimal control with flux variation, Cr= 5 N.m

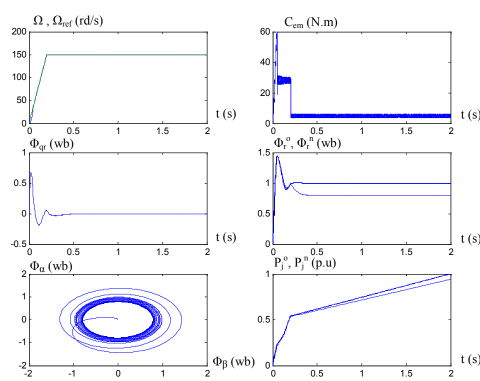

Fig.6. Simulation result of loss minimization, Cr=5N.m Comparison between nominal & optimal

C. Copper loss minimization with $i_{ds} = f(i_{qs})$

The optimization loss 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:

$$\Delta P_t = \sigma L_s \left(i_{ds} \frac{di_{ds}}{dt} + i_{qs} \frac{di_{qs}}{dt} \right) - \frac{L_m}{T_r L_r} \varphi_{dr} i_{ds} + \left(R_s + \frac{L_m^2}{L_r T_r} \right) \left(i_{ds}^2 + i_{qs}^2 \right) \tag{40}$$

In steady state, the minimum of power losses is reached for:

$$i_{ds} = \left(1 + \frac{L_m^2}{R_s L_r T_r} \right)^{\frac{1}{2}} i_{qs} \tag{41}$$

The behavior of the machine is simulated by using the block diagram of figure 7. The simulation results are presented on figure 8 under light load application. This method shows an important decrease in copper losses under low load torque.

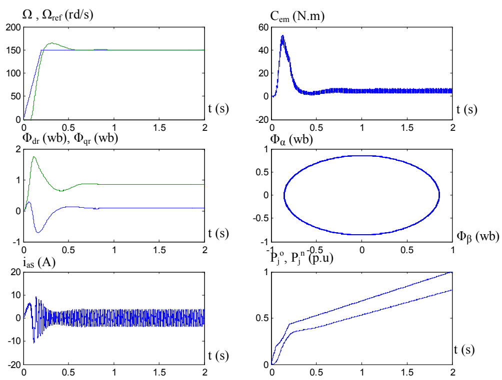

Fig.7. Simulation result of copper loss minimization, Cr=5N.m Comparison between nominal & optimal

D. Copper and iron loss minimization with $i_{ds} = f(i_{qs}, \omega)$

Loss Minimization is presented by introducing the mechanical phenomena. Copper and iron losses are given by:

$$\Delta P_t = R_s \left(i_{ds}^2 + i_{qs}^2 \right) + \frac{R_r R_{Fe}}{R_r + R_{fe}} i_{qs}^2 - \frac{L_m^2 \omega^2}{R_r + R_{fe}} i_{ds}^2 \tag{42}$$

$$i_{ds} = \sqrt{\frac{R_s R_r + R_s R_{fe} + R_r R_{fe}}{L_m^2 \omega^2 - R_s \left(R_r + R_{fe} \right)}} i_{qs}$$

(43)

The simulation results of Fig.8 shows a faster response time speed.

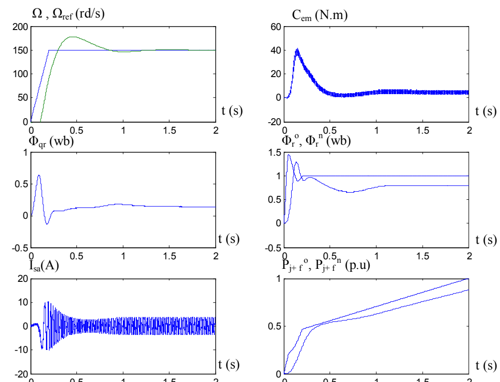

Fig.8. Simulation result of copper and iron loss minimization, Cr=5N.m Comparison between nominal & optimal

IV. CONCLUSION

In this work, we have presented a new method in reducing losses while considering and keeping under control machine parameters. This method could be important for the implementation in real time field oriented control. It has successfully demonstrated the design of vector field oriented control technique with optimum rotor flux using only the stator currents and position measurements. The main advantages of this method is that it is cheap and can be applied in both open and closed loop control.

APPENDICE

induction motor parameters: P_n= 1.5 kw,
U_n= 220 v, Ω_n= 1420 tr/mn, I_n= 3.64 A(Y) 6.31A(Δ),
R_s= 4.85Ω, R_r= 3.805Ω, L_s= 0.274 H, L_r= 0.274 H, p= 2,
L_m= 0.258 H, J= 0.031 kg.m ^{2}, f_r= 0.008 Nm.s/rd.

REFERENCES

[1] F. Abrahamsen, F. Blåbjer, J.K. Pederson, “Analysis of stability in low cost energy optimal controlled PWM VSI fed induction motor drive” in Proc. EPE’97 Trondheim Norway 1997, pp. 3.717-3.723.

[2] F. Abrahamsen, “Energy optimal control of induction motors” Ph.D. dissertation, Aalborg University, institute of energy technology, 1999.

[3] A.S. Bezanella, R. Reginetto, “Robust tuning of the speed loop in indirect field oriented control induction motors” Journal Automatica, Vol. 03, 2001, pp. 1811-1818.

[4] F. Blaschke, “The principle of field orientation as applied to the new transvector closed loop control system for rotating field machines” Siemens review, Vol. 34, May 1972, pp. 217-220.

[5] B.K. Bose, *Modern Power Electronics and AC Drives*. 2002, Prentice Hall.

[6] J. H. Chang, Byung Kook Kim,“ Minimum- time minimum – loss speed control of induction motors under field oriented control ” IEEE Trans. on Ind. Elec. Vol. 44, No. 6, Dec. 1997

[7] A. El-Refaei, S. Mahmoud, R. Kennel, “Torque Ripple Minimization for Induction motor Drives with Direct Torque Control (DTC)” Electric Power Components & systems, vol. 33, No.8, Aug. 2005

[8] J. Faiz, M.B.B. Sharifian,“ Optimal design of an induction motor for an electric vehicle ” Euro. Trans. Elec. Power 2006, 16: pp.15-33

[9] Y. Geng, G. Hua, W. Huangang, G. Pengyi, “A novel control strategy of induction motors for optimization of both efficiency and torque response” in Proc. The 30th annual conference of IEEE Ind. Elect. Society, Nov2-6, 2004, Busan, Korea, pp. 1405-1410.

[10] S. Grouni, R. Ibtiouen, M. Kidouche, O. Touhami, “Improvement rotor time constant in IFOC induction machine drives” International Journal of Mathematical, Physical and Engineering Sciences IJMPES, Vol. 2, No.1, Feb. 2008, pp. 126-131.

[11] J. Holtz, “Sensorless control of Induction Machines- with or without Signal Injection?” Overview Paper, IEEE Trans. on Ind. Elect. , Vol. 53, No.1, Feb. 2006, pp. 7-30.

[12] J. Holtz, J. Quan**,** “Sensorless control of induction motor drives” Proceedings of IEEE, Vol.(90), No.8, Aug. 2002, pp. 1359-1394.

[13] G.S. Kim, I.J. Ha, M.S. Ko, “Control of induction motors for both high dynamic performance and high power efficiency ” IEEE Trans. on Ind. Elect., Vol.39, No.4, 1988, pp. 192-199.

[14] I. Kioskeridis, N. Margaris, “Loss minimization in motor adjustable speed drives” IEEE Trans. Ind. Elec. Vol. 43, No.1, Feb. 1996, pp. 226-231.

[14] R. Krishnan “Electric Motor Drives, Modeling, Analysis and control” 2001, Prentice Hall.

[15] P. Krause, *Analysis of electric Machinery*, Series in Electrical Engineering, 1986, McGraw Hill, USA.

[16] E. Levi, “Impact of iron loss on behavior of vector controlled induction machines” IEEE Trans. on Ind. App., Vol.31, No.6, Nov./Dec. 1995, pp. 1287-1296.

[17] R.D. Lorenz, S.M. Yang, “AC induction servo sizing for motion control application via loss minimizing real time flux control theory” IEEE Trans. on Ind. App., Vol.28, No.3, 1992, pp. 589-593.

[18] J.C. Moreira, T.A. Lipo, V. Blasko, “Simple efficiency maximizer for an adjustable frequency induction motor drive” IEEE Trans. on Ind. App., Vol.27, No.5, 1991, pp. 940-945.

[19] J. J. Martinez Molina, Jose Miguel Ramirez scarpetta,“ Optimal U/f control for induction motors” 15th Triennial world congress, Barcelona, Spain, IFAC 2002.

[20] M. Rodic, K. Jezernik, “Speed sensorless sliding mode torque control of induction motor” IEEE Trans. on Industry electronics, Feb. 25, 2002, pp.1-15.

[21] T. Stefański, S. Karyś, “Loss minimization control of induction motor drive for electrical vehicle” ISIE’96, Warsaw, Poland, pp. 952-957

[22] S.K. Sul, M.H. Park, “A novel technique for optimal efficiency control of a current-source inverter-fed induction motor” IEEE Trans. on Pow. Elec., Vol.3, No.2, 1988, pp. 940-945.

[23] P. Vas, *Vector control of AC machines*.1990, Oxford Science Publications.