EFFICIENCY OPTIMIZED CONTROL FOR CLOSED-CYCLE OPERATIONS OF HIGH PERFORMANCE INDUCTION MOTOR DRIVE

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Abstract – *Algorithm for efficiency improvement of the high performance induction motor drive, based on the dynamic programming approach, is presented in this paper, along with performance index, constraints and system equations. For a given operating conditions in one periodical cycle, mathematical concept for optimal control is described so that the drive operates with minimal energy consumption. The procedure is described for a vector controlled induction motor drive, but procedures analogous to this one can be derived for other advanced techniques of induction motor drive control. Simulations and experimental tests have been performed.*

Key words *– Dynamic programming, Efficiency optimization, Induction motor drive, Loss model, Vector control*

1. Introduction

Undoubtedly, the induction motor is a widely used electrical motor and a great energy consumer. Three-phase induction motors consume more than 60% of industrial electricity and it takes a lot of effort to improve their efficiency [1]. Most of the motors operate at constant speed although the market for those of variable speed is expanding [2].

Moreover, induction motor drive (*IMD*) is often used in servo drive applications. Vector Control (*VC*) or Direct Torque Control (*DTC*) are the most commonly used control techniques in high-performance applications. These control methods enable software implementation of different algorithms for efficiency improvement.

Numerous scientific papers on the problem of loss reduction in *IMD* have been published in the last 20 years. Although good results have been achieved, there is still no generally accepted method for loss minimization. According to the literture, there are three strategies for dealing with the problem of efficiency optimization of the induction motor drive [3]:

- Simple State Control - *SSC* ,
- Loss Model Control - *LMC* and
- Search Control- *SC*.

The first strategy is based on the control of one of the variables in the drive [4-7] (fig. 1). This variable must be measured or estimated and its value is used in the feedback control of the drive, with the aim of running the motor by predefined reference value. Slip frequency or power factor displacement are the most often used variables in this control starategy.   Which one to chose depends on which measurement signals is available [3]. If slip frequency is used as control variable, information of rotor speed must be captured, regardless it is measured or estimated. Acquirement of the power factor requires measurement of the motor appearent and active input power or phase shift between stator voltage and current.   This strategy is simple, but gives good results only for a narrow set of operation conditions. Also, it is sensitive to parameter changes   in the drive due to temperature changes and magnetic circuit saturation.
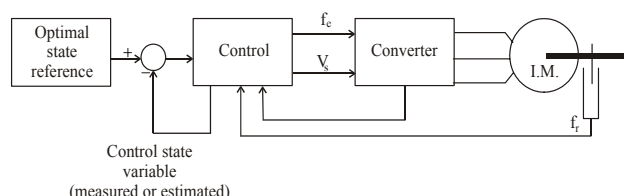

Fig. 1. Control diagram for the simple state efficiency
optimization startegy.

In the second strategy, a drive loss model is used for optimal drive control [8-12] (fig. 2). These algorithms are fast because the optimal control is calculated directly from the loss model. But, power loss modeling and calculation of the optimal operating conditions can be very complex. This strategy is also sensitive to parameter variations in the drive.
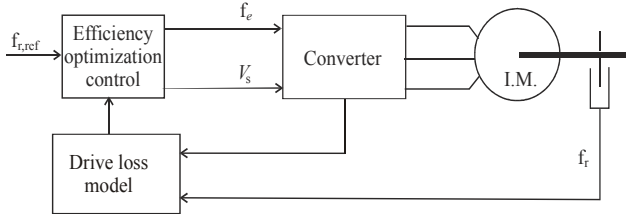

Fig. 2 Blok diagram for the model based control starategy.

In the search strategy, the on-line procedure for efficiency optimization is carried out [13-18] (fig. 3). The optimization variable, stator or rotor flux, increases or decreases step by step until the measured input power is at a minimum. This strategy has an important advantage over others: it is insensitive to parameter changes. The optimization does not require the knowledge of motor parameters and the algorithm is applicable universally to any motor. Besides all good characteristics of search strategy methods, there is an outstanding problem in its use. Flux in small steps oscillate around its optimal value. Sometimes convergation to its optimal value are to slow, so these methods are not applicable for high performance drives.
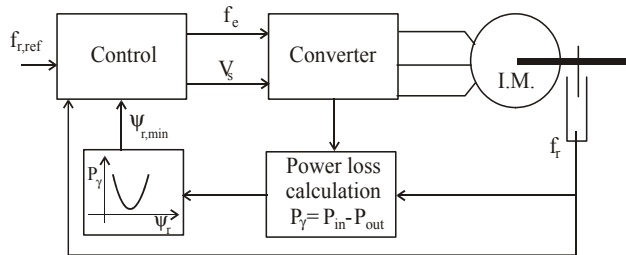

Fig. 3. Block diagram of search control startegy.

Also, there are hybrid methods which include good characteristics of different strategies for efficiency improvement [19].

The published methods mainly solve the problem of efficiency improvement for constant input power. There is an interesting question to ask, how these methods can be applied in the dynamic mode and what are problems and constrains. There are two distinctive cases: when the operation conditions are not known in advance and when they are.

In the cases when the operating conditions are not known in advance (e.g. electrical vehicles, cranes, etc.), it is important to watch for the electromagnetic torque margin and energy saving presents a compromise between power loss reduction and dynamic performances of the drive [20].

There are two common approaches when operation conditions are known in advance:

a) Steady state modified [21,22] and

b) Dynamic programming [21-23].

In the first case, the same methods, *LMC* or *SC* controllers, are used for steady state as well. Magnetizatizting flux is set to its nominal value during the dynamic transition [21], or a fuzzy controller is used to adjust the flux level in a machine by operation conditions [22, 23]. This can be realized in cases when torque or speed response is not so important (e.g. elevators or cranes). By using the dynamic programming approach, optimal control is computed so that the drive runs with minimal loss. The authors emphasize dynamic programming as a way to calculate optimal flux trajectories, but also discuss the problems of its application. Torque and speed trajectories have to be known in advance and flux trajectory has to be computed off-line, which requires a lot of processing time.

Also, an interesting problem is how to minimize energy consumption of IMD when it works in a periodic cycles. Closed-cycle operation are often for robots and other high performance industry machines. In this case problem of power loss minimization is more complex then for constant output power. Main goal is not minimization of power loss function (P_γ) for a given operating point, then minimization of integral of power loss function $\left(\int_0^T P_\gamma dt \right)$ for one cycle of machine.

Efficiency optimized control for closed-cycle operation of high performance IMD is described in this paper. Performance index, system equations and constraints for the variables have been defined. The mathematical concept for computing optimal control, based on the dynamic programming approach, is described in the second section. The results obtained through simulations and experiments as well as their comparison with the results achieved by *LMC* methods are presented in the third and fourth section respectively.

2. Algorithm for efficiency optimization of high performance induction motor drive

Efficiency improvement of *IMD* based on dynamic programming (optimal flux control) is an interesting solution for closed-cycle operation of drives [23]. For these drives, it is possible to compute optimal control, so the energy consuption for one operational cycle is minimized. In order to do that, it is necessary to define performance index, system equations and constraints for control and state variables and present them in a form suitable for computer processing [24,25].

The performance index is as follows:

$$J = \varphi[x(N)] + \sum_{i=1}^{N-1} L(x(i), u(i)) \qquad (1)$$

where $N = T/T_s$, T is a period of close-cycled operation and T_s is sample time. The L function is a scalar function of x-state variables and u-control variables, where $x(i)$, a sequence of n-vector, is determined by $u(i)$, a sequence of m-vector. The φ function is a function of state variables in the final stage of the cycle. It is necessary for a correct definition of performance index.

The system equations are:

$$x(i+1) = f[x(i), u(i)], \ i = 0..N-1, \qquad (2)$$

and f can be a linear or nonlinear function. Functions L and f must have first and second derivation on its domain.

The constraints of the control and state variables in terms of equality and inequality are:

$$C[x(i), u(i)] \leq 0, \quad i = 0,1,..,N-1. \qquad (3)$$

Following the above mentioned procedure, performance index, system equations, constraints and boundary conditions for a vector controlled *IMD* in the rotor flux oriented reference frame, can be defined as follows:

a) The performance index is [20, 26]:

$$J = \sum_{i=0}^{N-1} \left[a i_d^2(i) + b i_q^2(i) + c_1 \omega_e(i)\psi_D^2(i) + c_2 \omega_e^2(i)\psi_D^2(i) \right], (4)$$

where i_d, i_q: d and q are components of the stator current vector, ψ_D is rotor flux and ω_e is supply frequency. The a, b, c_1 and c_2 are parameters in the loss model of the drive. These parameters are determined through the process of paramater identification [20,26]. Rotor speed ω_r and electromagnetic torque T_{em} are defined by operating conditions (speed reference, load and friction).

b) The dynamics of the rotor flux can be described by the following equation:

$$\psi_D(i+1) = \psi_D(i)\left(1 - \frac{T_s}{T_r}\right) + \frac{T_s}{T_r} L_m i_d(i), \qquad (5)$$

where $T_r = L_r/R_r$ is a rotor time constant.

c) Constraints:

$$k i_d(i) i_q(i) = T_{em}(i), \ k = \frac{3}{2}\frac{p}{2}\frac{L_m^2}{L_r}, \ (for \ torque)$$

$$i_d^2(i) + i_q^2(i) - I_{s\max}^2 \leq 0, \ (for \ stator \ current)$$

$$-\omega_{rn} \leq \omega_r \leq \omega_{rn}, \ (for \ speed) \qquad (6)$$

$$\psi_D(i) - \psi_{Dn} \leq 0, \ (for \ rotor \ flux)$$

$$\psi_{D\min} - \psi_D(i) \leq 0.$$

I_{smax} is maximal amplitude of stator current, ω_{rn} is nominal rotor speed, p is number of poles, Ψ_{Dmin} is minimal and Ψ_{Dn} is nominal value of rotor flux.

Also, there are constraints on stator voltage:

$$0 \leq \sqrt{v_d^2 + v_q^2} \leq V_{s\max}, \qquad (7)$$

where v_d and v_q are components of stator voltage and V_{smax} is maximal amplitude of stator voltage.

Voltage constraints are more expressed in *DTC* than in field-oriented vector control.

d) Boundary conditions:

Basically, this is a boundary-value problem between two points which are defined by starting and final value of state variables:

$$\omega_r(0) = \omega_r(N) = 0,$$
$$T_{em}(0) = T_{em}(N) = 0,$$
$$\psi_{Dn}(0) = \psi_{Dn}(N) = free, \qquad (8)$$
$$considering \ constrains \ in \ (6)$$

Presence of state and control variables constrains generally complicates derivation of optimal control law. On the other side, these constrains reduce the range of values to be searched and simplify the size of computation [23].

Let us take the following assumptions into account:

1. There is no saturation effect ($\Psi_D \leq \Psi_{Dn}$).
2. Supply frequency is a sum of rotor speed and slip frequency, $\omega_e = \omega_r + \omega_s$. Rotor speed is defined by speed reference whereas slip frequency is usually low and insignificantly influences on total power loss [27].
3. Rotor leakage inductance is significantly lower than mutual inductance, $L_{\gamma r} \ll L_m$.

4. Electromagnetic torque reference and speed reference are defined by operation conditions within constraints defined in equation 6.

Following the dynamic programming theory [24, 25], Hamilitonian function H, including system equations and equality constrains can be written as follows:

$$H(i_d, i_d, \omega_e, \psi_D) = ai_d^2(i) + bi_q^2(i) +$$
$$c_1\omega_e(i)\psi_D^2(i) + c_2\omega_e^2(i)\psi_D^2(i) +$$
$$\lambda(i+1)\left[\psi_D(i)\frac{T_r - T_S}{T_r} + \frac{T_S}{T_r}L_m i_d(i)\right] \quad (9)$$
$$+ \mu(i)\left[ki_d(i)i_q(i) - T_{em}(i)\right].$$

In a purpose to determine stationary state of performance index, next system of differential equations are defined:

$$\lambda(i) = \lambda(i+1)\frac{T_r - T_S}{T_r} + 2\left(c_1\omega_e(i) + c_2\omega_e^2(i)\right)\psi_D(i)$$

$$2bi_q(i) + \mu(i)ki_d(i) = 0$$

$$2ai_d(i) + \mu(i)ki_q(i) + \lambda(i+1)\frac{T_S}{T_r}L_m = 0 \quad (10)$$

$$ki_d(i)i_q(i) = T_{em}(i), \ \omega_e(i) = \omega_r(i) + \frac{L_m}{T_r}\frac{i_q(i)}{\psi_D(i)}$$

$$i = 0, 1, 2, .., N - 1,$$

where λ and μ are Lagrange multipliers.

By solving the system of equations (10) and including boundary conditions given in (8), we come to the following system:

$$2ai_d^4(i) + \lambda(i+1)\frac{T_S}{T_r}i_d^3(i) = \frac{2b}{k^2}T_{em}^2(i)$$

$$\psi_D(i) = \frac{T_r}{T_r - T_s}\psi_D(i+1) - \frac{T_s}{T_r - T_s}L_m i_d(i)$$

$$i_q(i) = \frac{T_{em}(i)}{ki_d(i)}, \ \omega_e(i) = \omega_r(i) + \frac{L_m}{T_r}\frac{i_q(i)}{\psi_D(i)}, \quad (11)$$

$$\lambda(i) = 2\left(c_1\omega_e(i) + c_2\omega_e^2(i)\right)\psi_D(i) + \lambda(i+1)\frac{T_r - T_s}{T_r}$$

$$i = 0, 1, 2, .., N - 1.$$

Every sample time values of $\omega_r(i)$ and $T_{em}(i)$ defined by operating conditions is used to compute the optimal control $(i_d(i), i_q(i), i=0,..,N-1)$ through the iterative procedure and applying the backward procedure, from stage $i = N-1$ down to stage $i = 0$. For the optimal control computation, the final value of ψ_D and λ have to be known. In this case, $\psi_D(N) = \psi_{Dmin}$ and

$$\lambda(N) = \frac{\partial\varphi}{\partial\psi_D(N)} = 0. \quad (12)$$

Simulations and experiments have been performed in order to validate the proposed procedure.

3. Simulation results

The simulation tests have been performed by using Matlab.

Operation of the drive has been tested for closed-cycle operation. This usualy consist of three intervals: acceleration from 0 to ω_{ref}, interval $[0, t_1]$, constant speed $\omega = \omega_{ref}$, interval $[t_1, t_2]$, deceleration from ω_{ref} to 0, interval $[t_2, t_3]$. If the position of drive is not same in $t=0$ and $t=t_3$, one cycle consider fourth interval, return in a start position. Load torque changes at the moment $t_4=5$s from 0.4 p.u. to 1.05 p.u. and vice versa at the moment $t_5=10$s for aconstant reference speed of $\omega_{ref}=0.5$ p.u. (fig.4). The steep change of load torque appears with the aim of testing the drive behavior in the dynamic mode and its robustness within sudden load perturbations.
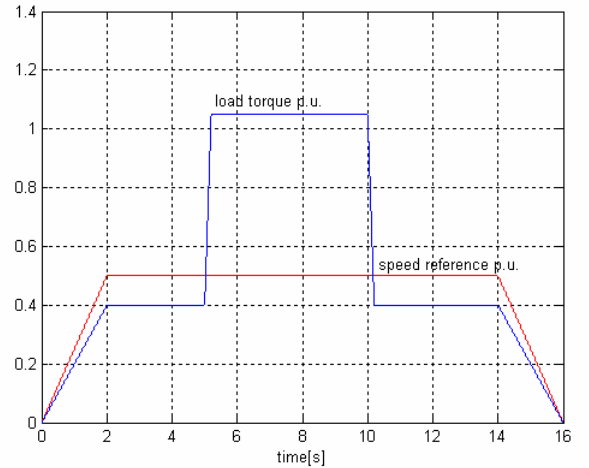

Fig. 4. Graph of speed and load torque reference.

Some drive variables such as output speed, magnetizing flux, electromagnetic torque and power loss have been captured in order to test the drive performances. The features of this algorithm have been compared with *LMC* model, which is fastest algorithm for efficiency improvement. Also, values of the drive variables have been captured when the drive runs with its nominal flux for the purpose of appraising the dynamic behavior of the drive when the algorithm for efficiency optimization is applied. The graph of optimal magnetizing flux is in fig. 5. Total power losses through a cycle and power losses during the transient process

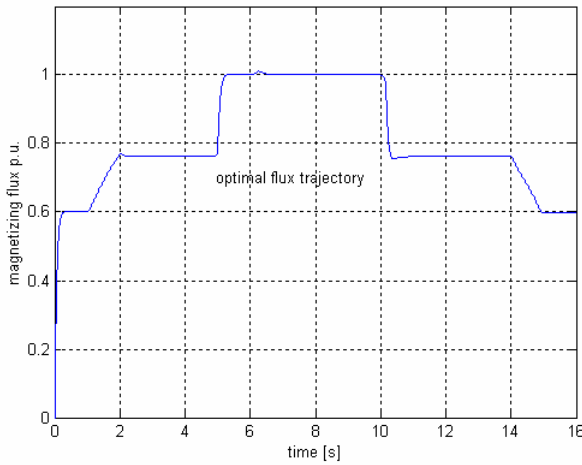for the steep change of load torque at t_4=5s are presented in fig. 6 and fig. 7 respectively.

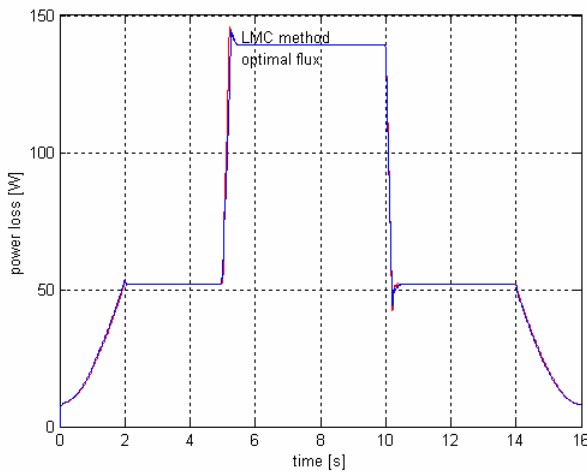Fig. 5. Optimal magnetizing flux during one operating cycle of drive.

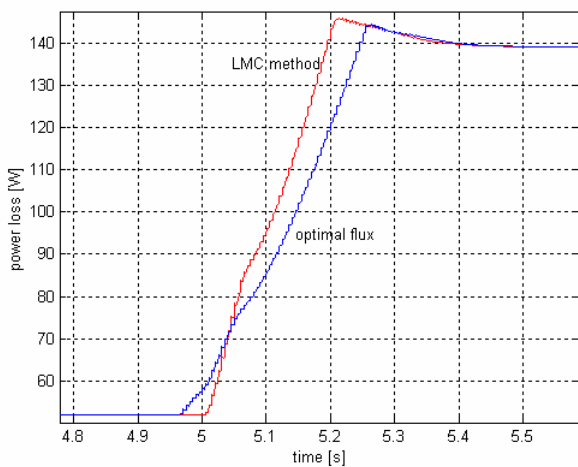

Fig. 6 Graph of total power losses.

Fig. 7. Graph of total power losses during transient process.

A higher value of magnetizing flux during the transient process in case of changing load or speed reference gives better dynamic features and less speed drops as it shown in fig. 8.
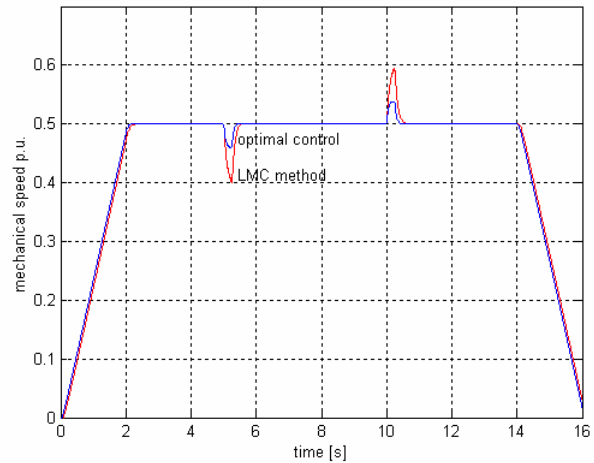

Fig. 8. Speed response to step change of load torque.

4. Experimental results

The experimental tests have been performed on the setup which consists of:
- induction motor (3 MOT, Δ380V/Y220V, 3.7/2.12A, cosϕ=0.71, 1400o/min, 50Hz)
- incremental encoder connected with the motor shaft,
- three-phase drive converter (DC/AC converter and DC link),
- PC and dSPACE1102 controller board with TMS320C31
  floating point processor and peripherals,
- interface between controller board and drive converter.

The algorithm observed in this paper used the Matlab – Simulink software, dSPACE real-time interface and C language. Handling real-time applications is done in ControlDesk.

All experimental tests and simulations have been done in the same operating conditions of the drive and some comparisons between algorithms for efficiency optimization are made through the experimental tests. For one typical operating cycle power losses are calculated in a three cases, when drive works with its nominal magnetizing flux, when LMC method is applied and for optimal flux control. Expressed problem in efficiency optimization methods are its sensitivity to steep increase of load or speed reference, especially for low flux level. Therefore, speed response on steep increase of load are analyzed for LMC and optimal flux control method.

Graph of power losses for a LMC method and optimal flux control and one operating cycle is presented in fig. 9.

Speed response on a steep load change for a LMC method and optimal flux are shawn in fig. 10.

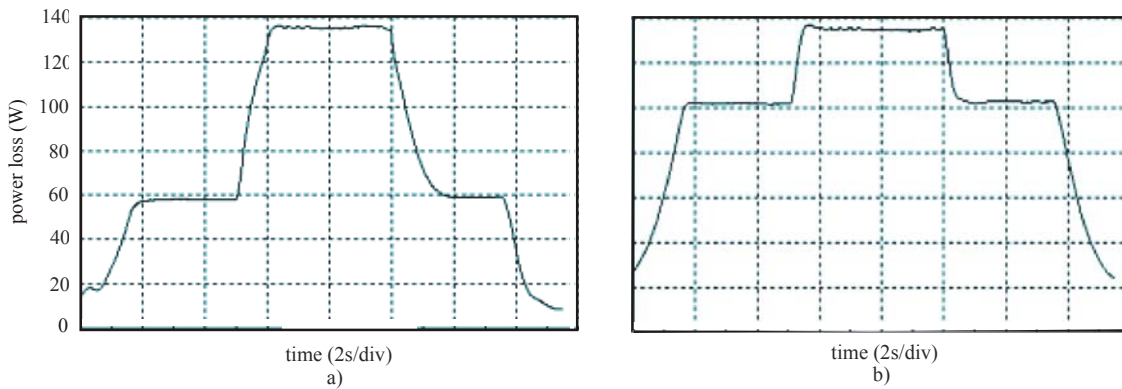Graph of optimal magnetizing flux is shown in fig.11

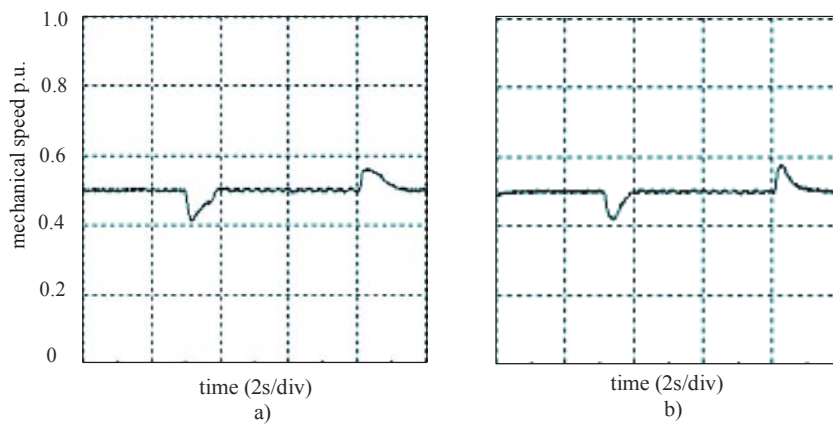Fig. 9 Power losses in one operating cycle for a) optimal flux b) nominal flux

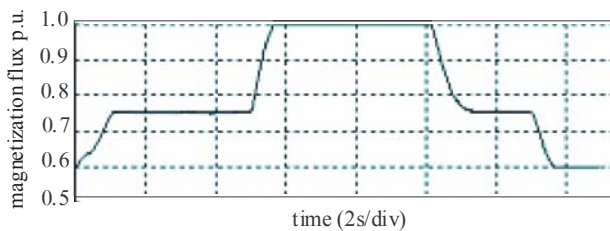Fig. 10 Speed response on steep load change for a) LMC method, b) optimal flux

Fig. 11. Optimal magnetizing fluks for one operating cycle.

The method for efficiency optimization based on the dynamic programming approach should show good results regarding the loss reduction during transient processes. Thus, it is very important to measure power losses in the drive for this method during the transient process and compare it with other efficiency optimization methods. The graphic of power losses for steep increase of load torque for optimal flux and LMC method is shown in fig. 12.
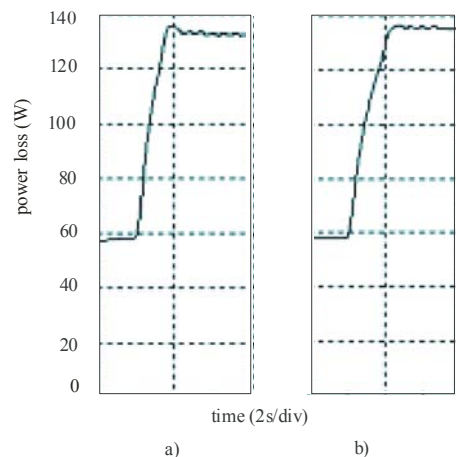

Fig. 12 Graph of power losses during transient process for a) LMC method, b) optimal control

The average value of power losses for every algorithm is computed and presented in Table 1.

Table 1
Average value of power losses

Applied method	Average value of power losses [W]
Nominal flux	86.548
LMC method	74.869
Optimal flux	73.36

Simulation and experimental tests are performed for typical closed-cycle operation, although this algorithm can be applied regardless of IMD operating conditions.

5. Conclusion

Algorithm for efficiency optimization of high performance induction motor drive and for closed-cycle operation has been described in this work. A procedure for optimal control computation has been applied. According to the performed simulations and experimental tests, we have arrived at the following conclusions:

1. If load torque has a value close to nominal or higher, magnetizing flux is also nominal regardless of whether an algorithm for efficiency optimization is applied or not. For a light load algorithm based on optimal flux control gives significant power loss reduction then when drive works with its nominal flux (fig. 9).

2. For a steady state, power losses are practically same for both methods, LMC and optimal flux control. but optimal flux control gives better results during transient prosess and consequently less energy consumption for one operating cycle then LMC methods. (figs. 7, 12 and table 1.).

3. Optimal flux control gives better dynamic features and less speed drops on steep load increase, then LMC methods (figs. 8 and 10)

4. The procedure of on-line parameter identification has been carried out in the background. In case the parameters change, a new optimal control value is computed for the next cycle of the drive operation.

This increases the robustness of the algorithm in response to parameter variations.

5. Few simplifications in the computation of optimal control for the dynamic programming method have been made (sec. 2). Therefore, the computation time is significantly reduced. Some theoretical and experimental results show that some effects like nonlinearity of magnetic circuit for $\Psi_D \leq \Psi_{Dn}$ has negligible influence in the calculation of optimal control.

6. One disadvantage of this algorithm is its off-line control computation. Yet, it is not complicated in terms of software.

The obtained experimental results show that this algorithm is applicable. It offers significant loss reduction, good dynamic features and stabile operation of the drive.

References

1. Kioskeridis I., Margaris N.: *Loss minimization in scalar controlled induction motor drives with search controllers*. In: IEEE Transaction on Power Electronics (1996) , Vol.11, No.2, 1996, pp. 213-220

2. Vukosavic S.N., *Controlled electrical drives - Status of technology*. In: Proceedings of XLII ETRAN Conference, Vrnjacka Banja, Yugoslavia, June 1998, No. 1, pp. 3-16,

3. Abrahamsen F, Pedersen JK, Blaabjerg F: *State-of-Art of optimal efficiency control of low cost induction motor drives*. In: Proceedings of PESC'96, 1996, pp. 920-924,

4. Hatanaka T, Kuwahara N: *Method and apparatus for controlling the supply of power to an induction motor to mainta in high efficiency under varying load conditions*, U.S. Patent 5 241 256, 1993

5. Moreira J.C., Lipo T.A. Blasko V.: *Simple Efficiency Maximizer for an Adjustible Frequency Induction Motor Drive*. In: IEEE Transaction on Industry Aplication (1991), Vol.27 , 1991, pp. 940-946

6. Benbouzid M.E.H., Nait Said N.S.: *An efficiency-optimization controller for induction motor drives*. In: IEEE Power Engineering Review (1998) , Vol. 18, Issue 5, 1998, pp. 63 –64

7. Yang S.M., Lin F.C.: *Loss-minimization control of vector-controlled induction motor drives*. In: Proceedings of IEEE International Conference on Power Electronics and Drive Systems , Vol. 1, 2001, pp. 182 -187,.

8. Mendes E., Razek A.: *A simple model for core losses and magnetic saturation in induction machines adapted for direct stator flux orientation control*. In: Proceedings of IEE/PECD'94, 1994, pp. 192-197

9. Pedersen J.K., Blabjerg F.: *An electrical car drive system using an energy-optimized control strategy based on an AC-machine and a microcontroller,* In: Proceedings of the 11th International Electrical Vehicle Symposium,*1992 ,* pp.12.031-1203.13

10. Fernandez-Bernal F., Garcia-Cerrada A., Faure R.: *Model-based loss minimization for DC and AC vector-controlled motors including core saturation* .In: IEEE Transactions on Industry Applications, (2000), Vol. 36, No. 3, 2000, pp. 755 -763

11. Prymak B., Moreno-Eguilaz J.A., Peracaula J.: *Neural network based efficiency optimization of an induction motor drive with vector control,* In: Proceedings of the

IECON 02 Industrial Electronics Society, IEEE 2002 28th Annual Conference , Vol. 1, pp. 146-151

12. Cao M.T., Hori Y.: *Convergence improvement of efficiency-optimization control of induction motor drives*. In: Industry Applications Conference, Conference Record of the 2000 IEEE, Vol. 3, pp. 1662 -1669,

13. Bose B.K., Patel N.R., Rajashekara K.: *A neuro fuzzy based on-line efficiency optimization control of a stator flux oriented direct vector controlled induction motor drive*, In: IEEE Transaction on Industrial Electronics (1997), Vol. 44, No.2, 1997, pp. 270-273

14. Sousa G.C.D., Bose B.K., Cleland J.G.: *Fuzzy logic based on-line efficiency optimization control of an indirect vector controlled induction motor drive.*, In: IEEE Transaction on Industrial Electronics (1995), Vol. 42, No.2, 1995, pp. 192-198

15. Cipola M., Moreno-Equilaz J.M., Peracula J.: *Fuzzy control of an induction motor with compensation of system dead-time.* In: Poceedings of the IEEE Power Electronics Specialist Conference, 1996, pp. 677-681

16. Raducanu I., Neacsu D.O.: *Novel hardware inference method for fuzzy logic controlled induction machine efficiency optimization*. In: Proceedings of the IEEE International Symposium on Industrial Electronics, ISIE '99., Vol. 2 , 1996, pp. 562 -567

17. Chis M., Jayaram S., Ramshaw R., Rajashekara K.: *Neural network based efficiency optimization of EV drive*. In: IEEE-IECIN Conference Record, 1997, pp. 454-457

18. Ghozzy S., Jelassi K., Roboam X.: *Energy optimization of induction motor drive*. In: International Conference on Industrial Technology, 2004. Conference Record of the 2004 IEEE, pp. 1662 -1669

19. Chakraborty C., Ta M.C., Uchida T., Hori Y.: *Fast search controllers for efficiency maximization of induction motor drives based on DC link power measurement*. In: Proceedings of the Power Conversion Conference 2002. PCC Osaka 2002., Vol. 2 , pp. 402 -408

20. Blanusa B., Matić P., Ivanovic Z, Vukosavic S.N.: *An Improved Loss Model Based Algorithm for Efficiency Optimization of the Induction Motor Drive*, In: Electronics (2006), Vol.10, No.1., 2006, pp. 49-52

21. Mendes E., Baba A., Razek A.: *Losses minimization of a field oriented controlled induction machine*. In: Electrical Machines and Drives, 1995. Seventh International Conference on (Conf. Publ. No. 412*)*, 1995, pp. 310 -314

22. Moreno J., Cipolla M., Peracaula J., Da Costa Branco P.J.: *Fuzzy logic based improvements in efficiency optimization of induction motor drives*. In: Proceedings of the Sixth IEEE International Conference on Fuzzy Systems, Vol. 1, 1997, pp. 219 - 224

23. Lorenz, R. D. Yang. S.-M.: *Efficiency –optimized flux trajectories for closed-cycle operation of field-orientation Induction Machine Drives*. In: IEEE Transactions on Industry Applications (1992), Vol.28, No.3, 1992, pp. 574-580

24. Bellman R., *Dynamic Programming*, Prinston University Press, 1957.

25. Brayson A. E., *Applied Optimal Control,Optimization, Estimation and Control*, John Wiley & Sons, 1975.

26. Vukosavić S.N., Levi E.: *Robust DSP-based efficiency optimization of variable speed induction motor drive*, IEEE Transaction of Ind. Electronics (2003), Vol. 50, No. 3, 2003, pp. 560-570

27. Ionel D.M., Popescu M., Dellinger S.J., Miller T.J.E., Heidiman R.J., McGilp M.I.: *On the variation with flux and frequency of the core loss coefficients in electrical machines*. In: IEEE Transactions on Industry Applications (2006), Vol. 42, No. 3, 2006, pp. 658-667