Algorithm for Efficiency Optimization of the Induction Motor Based on Loss Model and Torque Reserve Control

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Abstract - **New algorithm, based on loss model and torque reserve control, for efficiency optimization of the induction motor drive is presented in this paper. As a result, power and energy losses are reduced, especially when load torque is significant less compared to its nominal value. This algorithm can be used in high performance drive and present good compromise between power loss reduction and good dynamic characteristics. Simulation and experimental tests are performed.**

Key words- **Efficiency Optimization, Induction Motor Drive, Loss Model, Parameter Identification, Torque Reserve**

I. INTRODUCTION

Induction motor is without doubt the most used electrical motor and a great energy consumer [1]. Three-phase induction motors consume 60% of industrial electricity and it takes considerable efforts to improve their efficiency [1]. Most of the motors operate at constant speed although the market for variable speed is expanding. Moreover, induction motor drive (*IMD*) is often used in servo drive application. Vector control (*VC*) or Direct Torque Control (*DTC*) are the most often used control technique in the high performance applications.

There are numerous published papers which treated problem of efficiency optimization in the *IMD* in the last 20 years. Although, good results are achieved, there is no generally accepted method. There are three strategies which are usually used in the efficiency optimization of the induction motor drive [2]:

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

First strategy is based on the control one variable in the drive. This variable must be measured or estimated and its value is used in the feedback control to keep it on predefined reference value. This strategy is simple, but gives good results only for the narrower set of the working conditions. Also, it is sensitive to parameter changes due to parameter variations caused by temperature and saturation.

In the second strategy model of the power losses is used for the optimal control of drive. This is the fastest strategy, because the optimal control is calculated directly from the loss model. However, power loss modeling and calculation of the optimal operating point can be very complex. Also, this strategy is sensitive to parameter variations.

In the search strategy the on-line efficiency optimization control on the basis of search is implemented. Optimization variable, stator or rotor flux is decremented or incremented in steps until the measured input power settles down to the lowest value.

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This strategy has an important advantage compared to other strategies.It is completely insensitive to parameter changes. The control does not require 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 has never reached its nominal value, then in small steps oscillate around it. Sometimes convergation to optimal value can be to slow.

Very interesting problem for any optimization algorithm is its work with low flux level for a light load. When load is low, optimization algorithm settles down magnetization flux to make balance between iron and cooper losses and reduce total power losses. In this case drive is very sensitive to load perturbations.

LMC algorithm with on-line parameter identification in the loss model and torque reserve control implemented for indirect vector controlled *IMD* is proposed in this paper. Parameter identification is based on matrix calculation and Moore-Penrose pseudoinversion. Input power, output power and values of the variables in the loss model must be known. Torque reserve is determined on calculated reference flux from loss model and current and voltage constrains in machine. Algorithm for efficiency optimization is included in the model of *IMD* and both simulation and experimental studies are performed to validate theoretical development.

Functional approximation of the power losses in the induction motor drive is given in the second Section. Procedure of parameter identification in the loss model and calculation of optimal magnetization current are described in the third Section. Experimental results are presented in the fourth Section.

II. FUNCTIONAL APPROXIMATION OF THE POWER LOSSES IN THE INDUCTION MOTOR DRIVE

The process of energy conversion within motor drive converter and motor leads to the power losses in the motor windings and magnetic circuit as well as conduction and commutation losses in the inverter.

Converter losses: Main constituents of converter losses are the rectifier, DC link and inverter conductive and inverter commutation losses. Rectifier and DC link inverter losses are proportional to output power, so the overall flux-dependent losses are inverter losses. These are usually given by:

$$P_{INV} = R_{INV} \cdot i_s^2 = R_{INV} \cdot \left(i_d^2 + i_q^2\right), \tag{1}$$

where i_d, i_q are components of the stator current i_s in d,q rotational system and R_{INV} is inverter loss coefficient.

Motor losses: These losses consist of hysteresis and eddy current losses in the magnetic circuit (core losses), losses in the stator and rotor conductors (copper losses) and stray losses. At nominal operating point, the core losses are typically 2-3 times smaller then the cooper losses, but they represent main loss component of a highly loaded induction motor drives [3]. The main core losses can be modeled by [4]:

$$P_{Fe} = c_h \Psi_m^2 \omega_e + c_e \Psi_m^2 \omega_e^2 , \qquad (2)$$

where ψ_d is magnetizing flux, ω_e supply frequency, c_h is hysteresis and c_e eddy current core loss coefficient.

Copper losses are due to flow of the electric current through the stator and rotor windings and these are given by:

$$p_{Cu} = R_s i_s^2 + R_r i_q^2 , \qquad (3)$$

The stray flux losses depend on the form of stator and rotor slots and are frequency and load dependent. The total secondary losses (stray flux, skin effect and shaft stray losses) usually don't exceed 5% of the overall losses [3]. Formal omission of the stray loss representation in the loss function have no impact on the accuracy algorithm for on-line optimization.

Based on previous consideration, total flux dependent power losses in the drive are given by the following equitation:

$$P_\gamma = (R_{INV} + R_s) i_d^2 + (R_{INV} + R_s + R_r) i_q^2 + c_e \omega_e^{\,2} \psi_m^2 + c_h \omega_e \ \psi_m^2 . \quad (4)$$

Efficiency algorithm works so that flux in the machine is less or equal to its nominal value:

$$\psi_D \le \psi_{Dn,} \qquad (5)$$

where ψ_{Dn} is nominal value of rotor flux. So linear expression for rotor flux can be accepted:

$$\frac{d\psi_D}{dt} = \frac{R_r}{L_r} L_m i_d - \frac{R_r}{L_r} \psi_D , \qquad (6)$$

where $\Psi_D = L_m i_d$ in a steady state.

Expression for output power can be given as:

$$P_{out} = d\omega_r \psi_D i_q , \qquad (7)$$

where d is positive constant, ω_r angular speed, ψ_D rotor flux and i_q active component of the stator current. Based on previous consideration, assumption that position of the rotor flux is correctly calculated ($\Psi_Q = 0$) and relation $P_{in} = P_\gamma + P_{out}$ output power can be given by the following equation:

$$P_{in} = a i_d^2 + b i_q^2 + c_1 \omega_e^{\,2} \psi_D^2 + c_2 \omega_e \psi_D^2 + d\omega_r \psi_D i_q , \quad (8)$$

where a=R_s+R_{INV} , b= R_s+R_{INV}+R_r, c_1=c_e and c_2=c_h.

Input power should be measured and exact P_{out} is needed in order to acquire correct power loss and avoid coupling between load pulsation and the efficiency optimizer.

III. Determination of the Parameters in the Loss Model and Derivation of the Optimal Magnetization Current

Procedure of the parameter determination in the loss model is shown in Fig. 1. There is a modification in the procedure described in paper [3], so the iron losses is considered separately like hysteresis losses and eddy current losses. The inputs to the algorithms are samples of i_d^2 , i_q^2 , $\omega_e \psi_D^2, \omega_e^2 \psi_D^2, \omega_r \psi_D i_q$ and P_{in} and they are acquired every sample time, usually 100-200μs. As the high frequency components do not contribute identification W=[a b c_1 c_2 d]^T, input parameters and P_{in} are averaged within Q intervals $T = QT_S$. The averaging is implemented as the sum of Q consequetive samples of each signal (Fig.1). Column vectors P(:,1), P(:,2), P(:,3), P(:,4) and P(:,5) of matrix P_{Mx5} are created from the M successive values of A_N, B_N, C_{N1}, C_{N2}, D_N, N=1,..,M and vector Y_N is formed from the M averaged values of input power

$$\int_{nT}^{(n+1)T} P_{IN}(t)dt = a \int_{nT}^{(n+1)T} i_d^2(t)dt + b \int_{nT}^{(n+1)T} i_q^2(t)dt +$$
$$c_1 \int_{nT}^{(n+1)T} \left[\psi_D^2(t)\omega_e^2(t)dt\right] + c_2 \int_{nT}^{(n+1)T} \left[\psi_D^2(t)\omega_e(t)dt\right] +$$
$$d \int_{nT}^{(n+1)T} \left[i_q(t)\psi_D(t)\omega_r(t)dt\right]$$

$$Y_N = aA_N + bB_N + c_1 C_{N1} + c_2 C_{N2} + dD_N . \qquad (9)$$

Calculation of the vector W_g is based on Moore Penrose pseudoinverse of rectangular matrix P_{Mx5} [3]:

$$W_g = \left[a_g \, b_g \, c_g \, d_g\right]^T = (P^T P)^{-1} PY , \qquad (10)$$

and W_g is aproximative solution of matrix equation PW=Y, such the value of $\|PW - Y\|$ is minimum.

New vector W_g is usually calculated every 1.5-2s. The choice of Q is essential for the correct parameter identification. Credibility of W_g, relies on the excitation energy contained in the input signals. Hence, in absence of any disturbances, matrix $P^T P$ is getting near or being singular and values obtained from P should be discarded. In that case values of parameters are not changed and parameter determination is continued. For a known operational conditions of the induction motor (ω_r and T_{em}) and parameters in the loss model it is possible to calculate current i_d which gives minimum of the power losses [4].

Based on expression (4) power losses can be expressed in terms related to i_d, T_{em} and ω_s as follows

$$P_\gamma(i_d, T_{em}, \omega_e) = \left(a + c_1 L_m^2 \omega_e^2 + c_2 L_m^2 \omega_e\right) i_d^2 + \frac{bT_{em}^2}{(dL_m i_d)^2} . \quad (11)$$

Assuming absence of saturation and specifying slip frequency:

$$\omega_s = \omega_e - \omega_r = \frac{i_q}{T_r i_d} . \qquad (12)$$

power loss function can be expressed as function of current i_d and operational conditions (ω_r, T_{em}):

$$P_\gamma(i_d, T_{em}, \omega_r) = \left(a + c_1 L_m^2 \omega_r^2 + c_2 L_m^2 \omega_r\right) i_d^2 +$$
$$\frac{(2c_1\omega_r + c_2) L_m T_{em}}{dT_r} + \left(c_1 \frac{T_{em}^2}{(dT_r)^2} + \frac{bT_{em}^2}{(dL_m)^2}\right)\frac{1}{i_d^2} . \quad (13)$$

Based on equation (13), it is obvious, the steady-state optimum is readily found based upon the loss function parameters and operating conditions. Substituing $\alpha = \left(a + c_1 L_m^2 \omega_r^2 + c_2 L_m^2 \omega_r\right)$ and $\gamma = c_1 \dfrac{T_{em}^2}{d^2 T_r^2} + \dfrac{bT_{em}^2}{d^2 L_m^2}$ value of current i_d which gives minimal losses is:

$$i_{dopt} = \left(\frac{\gamma}{\alpha}\right)^{0.25} . \qquad (14)$$

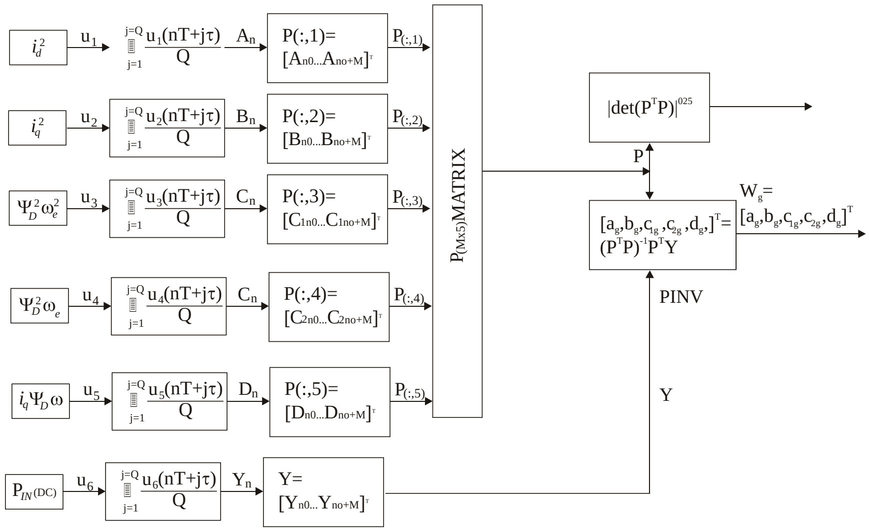

Fig 1. Determination of the parameters in the loss model from input signals.

Presented method is loss model based so it is fast [5]. Optimal value of magnetizing current is directly calculated from the model.

Online procedure of parameter identification is applied, so this method is robust on the parameter variations. One of the greatest problem of *LMC* methods is its sensitivity on load perturbation, especially for light loads when the flux level is low. This is expressed for a step increase of load torque and then two significiant problems appear:

1. Flux is far from its value during transient process, so transient losses are big.
2. Insufficiency in the electromagnetic torque leads output speed to converge slow to its reference value with significant speed drops. Also, oscillations in the speed response are appeared.

These are common problem of methods for efficiency optimization based on flux adjusting to load torque. Speed response on the step change of load torque (from 0.5 p.u. to 1.1 p.u.), for nominal flux and when *LMC* method is applied, is presented in the Figs. 2. Speed drops and slow speed convergence to its reference value are more exposed for *LMC* method.

These are reasons why torque reserve control in *LMC* method for efficiency optimization is necessary. Model of efficiency optimization controller with torque reserve control is presented in Fig. 3. Optimal value of magnetization current is calculated from the loss model and for given operational conditions Eq. (14). Increment of magnetizing current (Δid) is generated from the fuzzy rules through the fuzzy inference and defuzzification, on the basis of the previously determined torque reserve (ΔT_{em}). Fuzzy logic controller is used in determination of Δi_d. Controller is very simple, and there is one input, one output and 3 rules. Only 3 membership functions are enough to describe influence of torque reserve in the generation of i^*_{dopt}.

If torque reserve is sufficient then $\Delta i_d \approx 0$ and this block has no effect in a determination of i^*_{dopt}. Oppositely, current i_d (magnetization flux) increases to obtain sufficient reserve of electromagnetic torque.

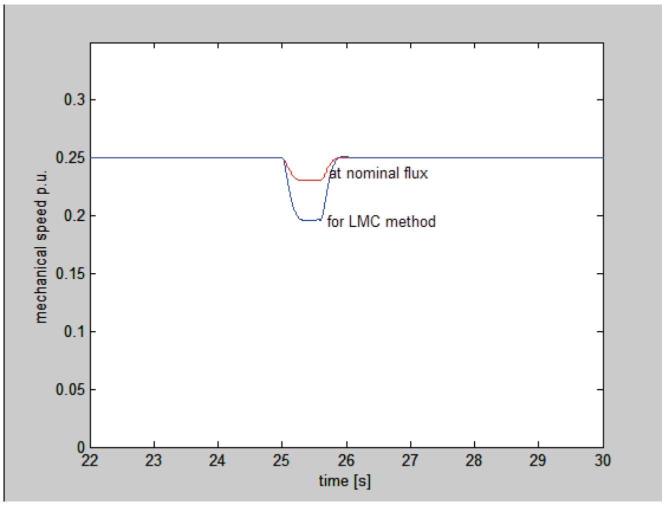

Fig. 2. Speed response on the step load increase for nominal flux and when LMC is applied.

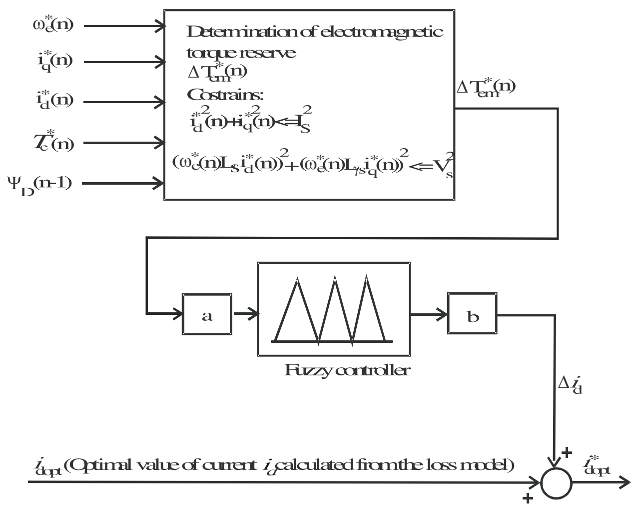

Fig. 3. Block for efficiency optimization with torque reserve control.

Two scaling factors are used in efficiency controller [6]. Factor *a* is used for normalization of input variable, so same controller can be used for a different power range of machine. Factor *b* is output scaling factor and it is used to adjust influence of torque reserve in determination of i^*_{dopt} and obtain requested compromise between power loss reduction and good dynamic response.

IV. EXPERIMENTAL RESULTS

Experimental tests were performed on the Laboratory Station for Vector Control of the Induction Motor Drives -Vectra. Basic parts of the Laboratory Station Vectra are:

- 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.

Control and acquisition function as well as signal processing are executed on this board, while PC provides comfortable interface toward user.

Algorithms observed in this paper is software realized using Matlab – Simulink, C and real-time interfac*e* for dSPACE hardware. Handling real-time applications is done in ControlDesk.

Power losses and speed response of the motor drive with and without applied algorithm for torque reserve control are presented in Figs. 4. and 5. respectively. The load torque step changes in t_1=25s from 0.5 p.u. to 1.0 p.u. and vice versa in t_2=50s at constant reference speed ω_{ref}=0.2 p.u.

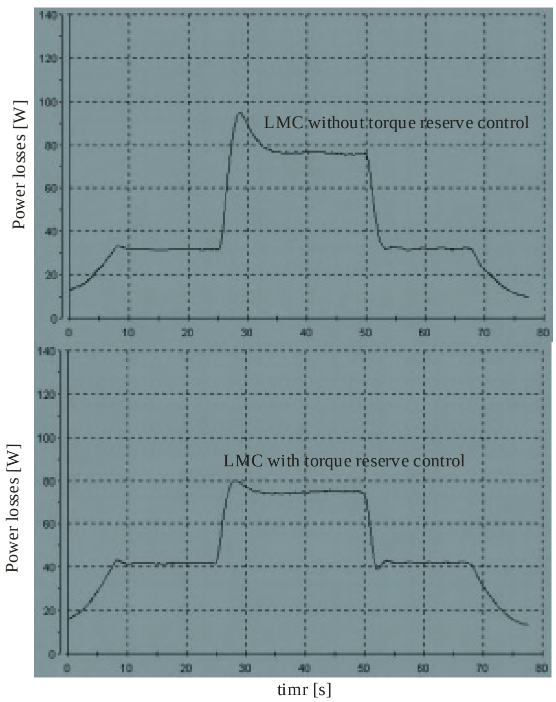

Fig. 4. Graphics of power losses for a step change of load torque.

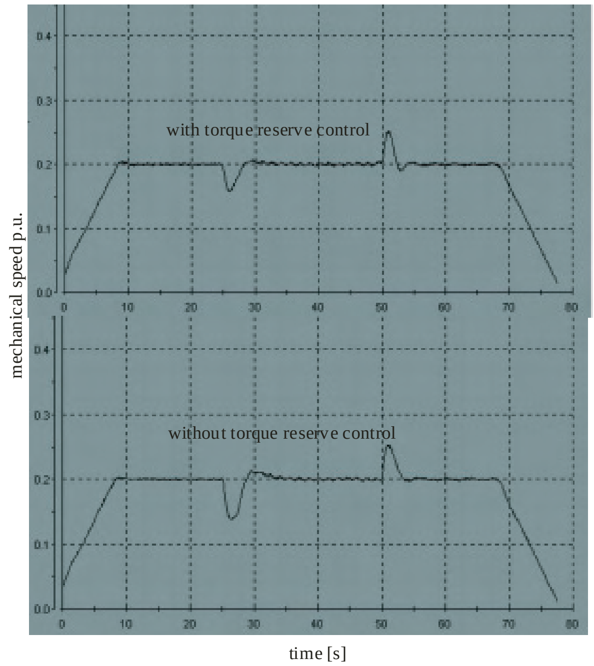

Fig. 5. Graphics of mechanical speed for a step change of load torque.

V. CONCLUSION

By implementation of *LMC* method with torque reserve control next results are reached:

1. Less sensitivity on load perturbation compared to standard *LMC* methods without torque reserve control.
2. Better control characteristics
3. Less transient losses

Algorithm with torque reserve control gives negligible higher losses in a steady state then standard *LMC* methods.

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