Efficiency Optimized Control of High Performance Induction Motor Drive

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Abstract—**Algorithms for efficiency optimized control of induction motor drives are presented in this paper. As a result, power and energy losses are reduced, especially when load torque is significant less compared to its rated value. According to the literture, there are three strategies for dealing with the problem of efficiency optimization of the induction motor drive: Simple State Control, Loss Model Control and Search Control. Basic characteristics each of these algorithms and their implementation in induction motor drives are described. Moreover, induction motor drive is often used in a high performance applications. Vector Control or Direct Torque Control are the most commonly used control techniques in these applications. These control methods enable software implementation of different algorithms for efficiency improvement. Simulation and experimental tests for some algorithms are performed and results are presented.**

Index Terms—**Induction motor, efficiency optimization, dynamic programming.**

I. 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]. The vast majority of induction motor drives are used for heating, ventilation and air conditioning (HVAC). These applications require only low dynamic performance and in most cases only voltage source inverter is inserted between grid and induction motor as cheapest solution. The classical way to control these dives is constant V/f ratio and simple methods for efficiency optimization can be applied [2]. From the other side in applications like electric vehicle energy has to be consumed in the best possible way and use of induction motors in such application requires an energy optimized control strategy [3]. Also, there are many high performance industrial drives which operate in periodic cycles. In these cases implementation of efficiency optimization algorithm are more complex.

In a conventional setting, the field excitation is kept constant at rated value throughout its entire load range. If machine is under-loaded, this would result in over-excitation and unnecessary copper losses. Thus in cases where a motor drive has to operate in wider load range, the minimization of losses has great significance. It is known that efficiency improvement of induction motor drive (*IMD*) can be implemented via motor flux level and this method has been proven to be particularly effective at light loads and in a steady state of drive. Moreover, induction motor drive is often used in servo drive applications. Vector Control (*VC*) or Direct Torque Control (*DTC*) are the most commonly used control techniques in such applications and these methods enable software implementation of different algorithms for efficiency improvement.

Functional approximation of the power losses in the vector controlled induction motor drive is given in the second Section. Strategies for efficiency optimization of IMD and their basic characteristics are described in third section. Qualitative analysis and comparison of interesting algorithms for efficiency optimization with simulation and experimental results are presented in fourth section. Brief description of efficiency optimized control of high performance IMD is described in fifth 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 [4].

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:

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

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. The main core losses can be modeled by:

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

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

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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 [4].

III. STRATEGIES FOR EFFICIENCY OPTIMIZATION OF IMD

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 literature, there are three strategies for dealing with the problem of efficiency optimization of the induction motor drive [5]:

- 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 [5-7] (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 strategy. Which one to chose depends on which measurement signals is available [5]. 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.

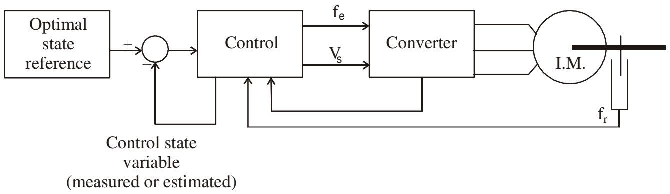

Fig. 1. Control diagram for the simple state efficiency.

In the second strategy, a drive loss model is used for optimal drive control [4,8] (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.

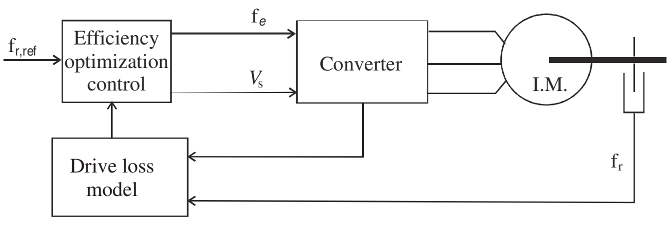

Fig. 2. Block diagram for the model based control strategy.

In the search strategy, the on-line procedure for efficiency optimization is carried out [9-11] (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.

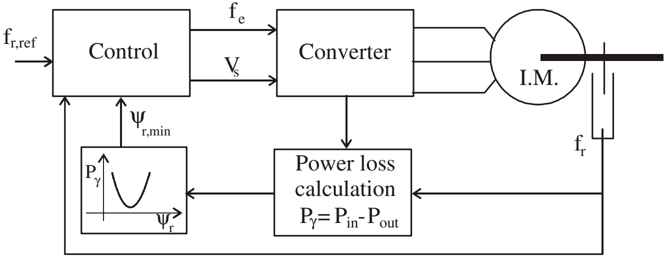

Fig. 3. Block diagram of search control strategy.

Also, there are hybrid methods which include good characteristics of different strategies for efficiency improvement [10].

The published methods mainly solve the problem of efficiency improvement for constant output power. Results of applied algorithms highly depends from the size of drive (Fig. 4) [2] and operating conditions, especially load torque and speed (Figs. 5 and 6). Efficiency of IM changes from 75% for low power 0,75kW machine to more than 95% for 100kW machine. Also efficiency of drive converter is typically 95% and more.

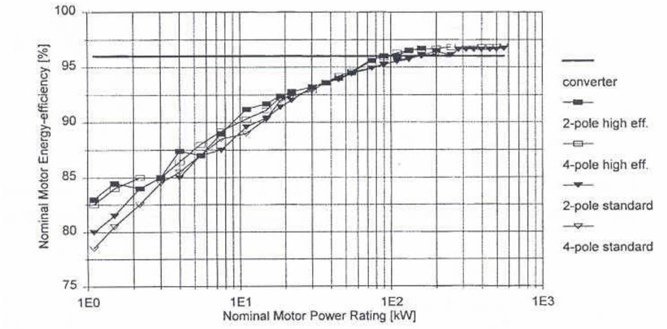

Fig. 4. Rated motor efficiences for ABB motors (catalog data) and typical converter efficiency.

That's obvious, converter losses is not necessary to consider in efficiency optimal control for small drives. Also, these algorithms for efficiency optimization give best result in power losses reduction for a light loads and in a steady state.

IV. COMPARISON OF SOME ALGORITHMS FOR EFFICIENCY OPTIMIZATION OF IMD

Selection of algorithm for efficiency optimization depends from many factors, drive features, operating conditions, measuring signals, drive control and etc.

If the losses in the drive were known exactly, it would be possible to calculate the optimal operating point and control of drive in accordance to that. For the following reasons it is not possible in practice [9]:

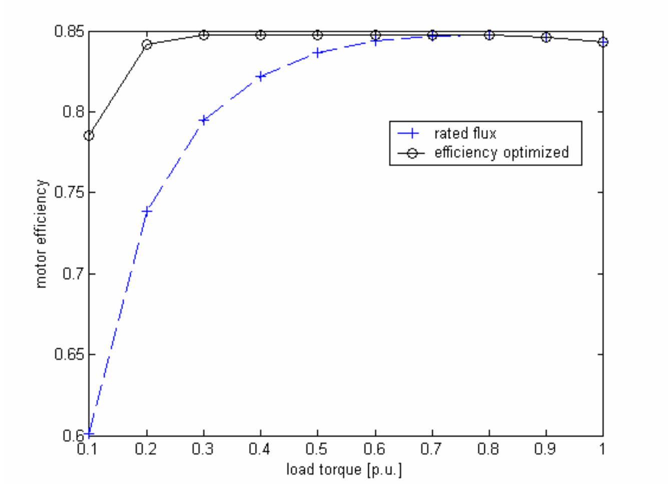

Fig. 5. Measured standard motor efficiencies with both rated flux and efficiency optimized control at rated mechanical speed (2.2 kW rated power).

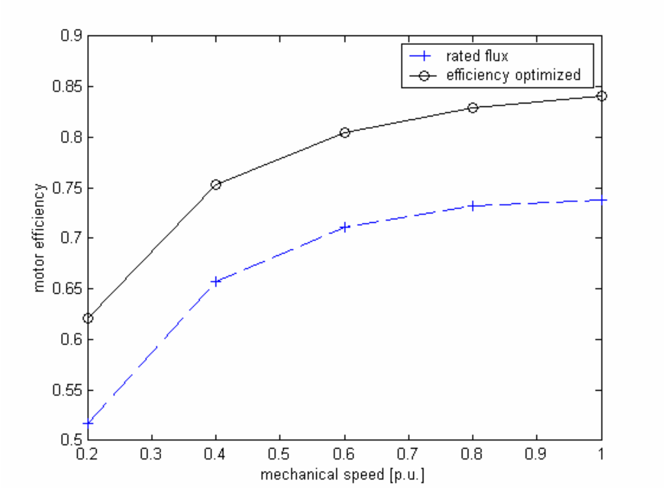

Fig. 6. Measured standard motor efficiencies with both rated flux and efficiency optimized control at light load (20% of rated load).

- A number of fundamental losses are difficult to predict: stray load, iron losses in case of saturation changes, copper losses because of temperature rise etc.
- Due to limitation in costs all the measurable signals cannot be acquired. It means that certain quantities must be estimated which naturally leads to an error.

Two interesting algorithms *SC* and *LMC* are discussed and their results in efficiency optimization are compared for different operating conditions. Also, power losses for these algorithms are presented together with a case when motor is excited by rated magnetizing flux. Operation of drive has been tested under following operating conditions. There are 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]. Load torque changes at the moment t_4=5s from 0.4 p.u. to 1.05 p.u. and vice versa at the moment t_5=10s for a constant reference speed of ω_{ref}=0.6 p.u. (Fig.7). 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.

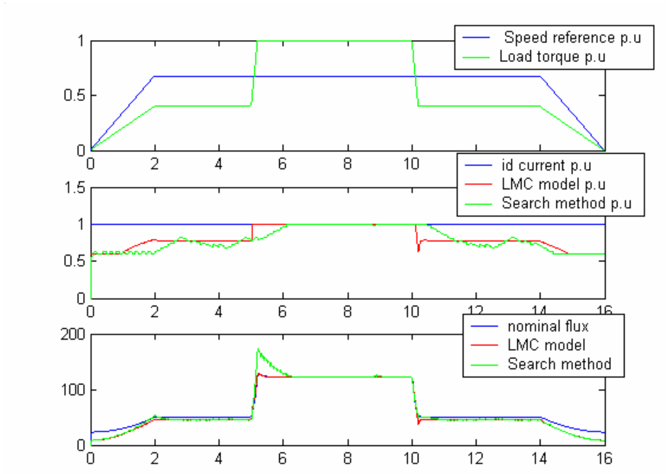

Fig. 7. Comparison of SC and LMC algorithms for efficiency optimization in IMD.

Simulation tests show that LMC algorithm is faster than SC algorithm and gives better result in power loss reduction than SC algorithm. Optimal magnetizing flux is derived directly from the loss model of IMD. Loss modeling, optimal flux calculation and especially its sensitivity to parameter changes are problems which limits implementation of this control strategy. But LMC algorithm with on-line parameter identification in the loss model and hybrid models make this strategy very actual [4].

From the other side search strategy 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 oscillates around its optimal value. Torque ripple appears each time the flux is stepped. Sometimes convergence to its optimal value is to slow, so these methods are not applicable for high performance drives. There are numerous papers which treats problem of step size in the magnetization flux for SC algorithms. Fuzzy or neuro-fuzzy controllers are often used to obtain smooth and fast flux convergence during optimization process [9,10].

V. EFFICIENCY OPTIMIZATION IN DYNAMIC OPERATION

There is an interesting question to ask, how algorithms for efficiency optimization 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 [12].

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

a) Steady state modified [13,14] and

b) Dynamic programming [13-15].

In the first case, the same methods, LMC or SC controllers, are used for steady state as well. Magnetizing flux is set to its nominal value during the dynamic transition [13], or a fuzzy controller is used to adjust the flux level in a machine by operation conditions [13, 14]. This can be realized in cases when torque or speed response is not so important (e.g. elevators or cranes).

If the both high dynamic performance and losses minimization are required dynamic optimization is necessary. By using the dynamic programming approach, optimal control is computed so that the drive runs with minimal losses. 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 is often for robots and other high performance industry machines. Efficiency optimized control for closed-cycle operation of high performance IMD, based on dynamic programming approach is applied.

Following dynamic programming approach, 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 [12, 16]:

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

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 parameter identification [4,12]. 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:

$$\psi_D(i+1)=\psi_D(i)\left(1-\frac{T_s}{T_r}\right)+\frac{T_s}{T_r}L_m i_d(i), \quad (2)$$

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

c) Constraints:

$$\begin{aligned}
&k i_d(i) i_q(i)=T_{em}(i),\ k=\frac{3}{2}\frac{p}{2}\frac{L_m^2}{L_r},\ (for\ torque)\\
&{i_d}^2(i)+{i_q}^2(i)-I_{s\max}^2\le 0,\ (for\ stator\ current)\\
&-\omega_{rn}\le\omega_r\le\omega_{rn},\ (for\ speed)\\
&\psi_D(i)-\psi_{Dn}\le 0,\ (for\ rotor\ flux)\\
&\psi_{D\min}-\psi_D(i)\le 0.
\end{aligned} \quad (3)$$

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:

$$0\le\sqrt{v_d^2+v_q^2}\le V_{s\max}, \quad (4)$$

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:

$$\begin{aligned}
&\omega_r(0)=\omega_r(N)=0,\\
&T_{em}(0)=T_{em}(N)=0,\\
&\psi_{Dn}(0)=\psi_{Dn}(N)=free,\\
&considering\ constrains\ in\ (3)
\end{aligned} \quad (5)$$

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 [17].

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

$$\begin{aligned}
&\lambda(i)=\lambda(i+1)\frac{T_r-T_S}{T_r}+2\left(c_1\omega_e(i)+c_2\omega_e^2(i)\right)\psi_D(i)\\
&2b i_q(i)+\mu(i)k i_d(i)=0\\
&2a i_d(i)+\mu(i)k i_q(i)+\lambda(i+1)\frac{T_S}{T_r}L_m=0\\
&k i_d(i) i_q(i)=T_{em}(i),\ \omega_e(i)=\omega_r(i)+\frac{L_m}{T_r}\frac{i_q(i)}{\psi_D(i)}\\
&i=0,1,2,..,N-1,
\end{aligned} \quad (6)$$

where λ and μ are Lagrange multipliers.

By solving the system of equations (6) and including boundary conditions given in (5), we come to the following system [16]:

$$\begin{aligned}
&2a i_d^4(i)+\lambda(i+1)\frac{T_S}{T_r}i_d^3(i)=\frac{2b}{k^2}T_{em}^2(i)\\
&\psi_D(i)=\frac{T_r}{T_r-T_s}\psi_D(i+1)-\frac{T_s}{T_r-T_s}L_m i_d(i)\\
&i_q(i)=\frac{T_{em}(i)}{k i_d(i)},\omega_e(i)=\omega_r(i)+\frac{L_m}{T_r}\frac{i_q(i)}{\psi_D(i)},\\
&\lambda(i)=2\left(c_1\omega_e(i)+c_2\omega_e^2(i)\right)\psi_D(i)+\lambda(i+1)\frac{T_r-T_s}{T_r}\\
&i=0,1,2,..,N-1.
\end{aligned} \quad (7)$$

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

$$\lambda(N)=\frac{\partial\varphi}{\partial\psi_D(N)}=0. \quad (8)$$

Expressed problem in efficiency optimization methods are its sensitivity to steep increase of load or speed reference, especially for low flux level. Therefore, some experiments are made to appraise speed response on steep increase of load for LMC and optimal flux control method (Fig. 8).

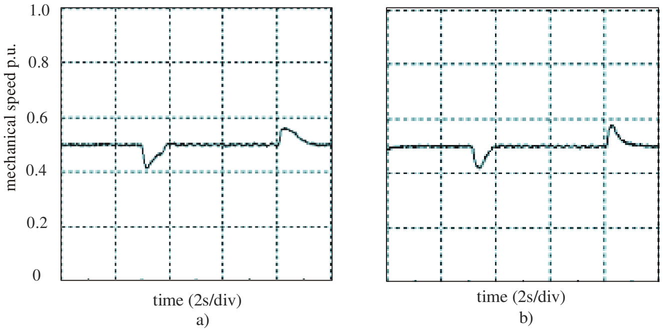

Fig. 8. Speed response on steep load change for a) LMC method, b) optimal flux.

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. 9.

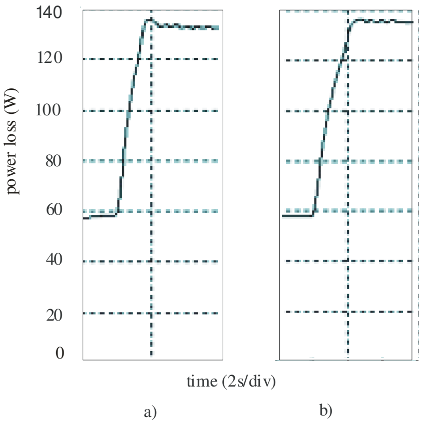

Fig. 9. Graph of power losses during dynamic operation for a) LMC method, b) optimal control.

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

VI. CONCLUSION

Algorithms for efficiency optimization of IMD are briefly described and some comparison between LMC and SC strategies are made. Also, one procedure for efficiency optimization in dynamic operation based on dynamic programming approach 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 significiant power loss reduction when drive works with its nominal flux (Figs. 5, 6 and 7).

2. For a steady state, power losses are practically same for both methods, SC and LMC, but SC algorithms give faster convergence of magnetizing flux during transient prosess and consequently less energy consumption. (Fig. 7). From the other side SC algorithms do not require knowledge of motor parameters and not sensitive to motor parameters changes.

3. Optimal flux control based on dynamic programming gives better dynamic features and less speed drops on steep load increase, then LMC methods (Figs. 8 and 9). The obtained experimental results show that this algorithm is applicable. It offers significant loss reduction, good dynamic features and stable operation of the drive. One disadvantage of this algorithm is its off-line control computation.

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