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 literature, 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 strategy. Which one to choose 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. Acquisition of the power factor requires measurement of the motor apparent 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 strategy.**
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 strategy.

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 convergence to its optimal value are too slow, so these methods are not applicable for high performance drives.

Fig. 3. Block diagram of search control strategy.

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. Magnetizing 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 \( P_L \) for a given operating point, then minimization of integral of power loss function \( \int_0^T P_L \, dt \) 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 constrains 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 consumption 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:

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

(1)

where \( N=TT \), \( T \) 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 \( \phi \) 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:

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

(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:

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

(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]:

\[ J = \sum_{i=0}^{N-1} \left[ u_d^2(i) + b_1^2 c_3 a_1^2 \psi_d^2(i) + c_2 a_1^2 \psi_d^2(i) \right], \]  

(4)

where \( i_d \), \( i_q \): \( d \) and \( q \) components of the stator current vector, \( \psi_d \) is rotor flux and \( \omega_r \) is supply frequency. The a, b, c1 and c2 are parameters in the loss model of the drive. These parameters are determined through the process of parameter identification [20,26]. Rotor speed \( \omega_r \) 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:

\[ \psi_d(i+1) = \psi_d(i) \left( 1 - \frac{T_r}{T_s} \right) + \frac{T}{T_r} L_{m} i_d(i), \]  

(5)

where \( T_r = L_{mr} / R \), is a rotor time constant.

c) Constraints:

\[ k_i(i) = \frac{\psi_d(i)}{\psi_d(i)}, \quad k = \frac{2}{2}, \quad \text{(for torque)} \]

\[ i_d(i) + i_i(i) - I_{max} \leq 0, \quad \text{(for stator current)} \]

\[ -\omega_b \leq \omega_r \leq \omega_B, \quad \text{(for speed)} \]

\[ \psi_{Dn} \Psi \leq \psi_{Dn}, \quad \text{(for rotor flux)} \]

\[ \psi_{Dn}, \psi_{D1} \leq 0. \]

\( L_{max} \) is maximal amplitude of stator current, \( \omega_b \) is nominal rotor speed, \( p \) is number of poles, \( \psi_{Dn} \) is minimal and \( \psi_{Dn} \) is nominal value of rotor flux.

Also, there are constraints on stator voltage:

\[ 0 \leq \sqrt{v_d^2 + v_q^2} \leq V_{max}, \]  

(7)

where \( v_d \) and \( v_q \) are components of stator voltage and \( V_{max} \) 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:

\[ \omega_r(0) = \omega_r(N) = 0, \]

\[ T_{em}(0) = T_{em}(N) = 0, \]

\[ \psi_{Dn}(0) = \psi_{Dn}(N) = \text{free}, \]  

(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 (\( \Psi_s \leq \Psi_{Dn} \)).
2. Supply frequency is a sum of rotor speed and slip frequency, \( \omega_r = \omega_r + \omega_s \). 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, \( L_{pr} \ll L_{mr} \).
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], Hamiltonian function H, including system equations and equality constrains can be written as follows:

\[
\begin{align*}
H(i_d, i_s, \omega_r, \psi_D) &= ai_d^2(i) + bi_d^2(i) + c_i \omega_r(i) \psi_D^2(i) + c_s \omega_s^2(i) \psi_D^2(i) + \\
& \lambda(i + 1) \left[ \psi_D(i) \frac{T_s - T_d}{T_r} + \frac{T_s}{T_r} L_m i_d(i) \right] + \mu(i) [k_d(i) i_d(i) - T_m(i)].
\end{align*}
\]

(9)

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

\[
\begin{align*}
\lambda(i) &= \lambda(i + 1) \frac{T_s - T_d}{T_r} + 2(c_i \omega_r(i) + c_s \omega_s^2(i)) \psi_D(i) + 2b_i q(i) + \mu(i) k_i q(i) = 0 \\
2ai_d(i) + \mu(i) k_i q(i) + \lambda(i + 1) \frac{T_s}{T_r} L_m = 0 \\
2ai_d(i) + \lambda(i + 1) \frac{T_s}{T_r} L_m = 0
\end{align*}
\]

(10)

\[
\begin{align*}
k_i q(i) &= T_m(i), \quad \omega_r(i) = \omega_r(i) + \frac{L_m i_d(i)}{T_r} \psi_D(i) \\
i_q(i) &= T_m(i), \quad \omega_r(i) = \omega_r(i) + \frac{L_m i_d(i)}{T_r} \psi_D(i)
\end{align*}
\]

(11)

where \(\lambda\) and \(\mu\) are Lagrange multipliers.

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

\[
\begin{align*}
2ai_d(i) + \lambda(i + 1) \frac{T_s}{T_r} i_d^2(i) &= \frac{2b_i}{k_i} T_m^2(i) \\
\psi_D(i) &= \frac{T_r}{T_s} \psi_D(i + 1) - \frac{T_s}{T_r} - T_m(i) \\
i_q(i) &= \frac{T_m(i)}{k_i q(i)}, \quad \omega_r(i) = \omega_r(i) + \frac{L_m i_d(i)}{T_r} \psi_D(i)
\end{align*}
\]

(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 usually consist of three intervals: acceleration from 0 to \(\omega_{ref}\), interval \([0, t_i]\), constant speed \(\omega=\omega_{ref}\), interval \([t_i, t_2]\), deceleration from \(\omega_{ref}\) to 0, interval \([t_2, t_3]\). If the position of drive is not same in \(r=0\) and \(r=r_{sys}\) one cycle consider fourth interval, return in a start position. Load torque changes at the moment \(t_r=5s\) from 0.4 p.u. to 1.05 p.u. and vice versa at the moment \(t_r=10s\) 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.

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 \( t_4 = 5 \text{s} \) are presented in fig. 6 and fig. 7 respectively.

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

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, \( \Delta 380\text{V}/\text{Y} 220\text{V}, 3.7/2.12\text{A,} \cos \phi = 0.71, 1400\text{r/min,} 50\text{Hz} \))
- 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 shown in fig. 10. Graph of optimal magnetizing flux is shown in fig. 11.

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.

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

<table>
<thead>
<tr>
<th>Applied method</th>
<th>Average value of power losses [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal flux</td>
<td>86.548</td>
</tr>
<tr>
<td>LMC method</td>
<td>74.869</td>
</tr>
<tr>
<td>Optimal flux</td>
<td>73.36</td>
</tr>
</tbody>
</table>

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 results, 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 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 processes 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 $\Psi_D < \Psi_{Dn}$ 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 stable operation of the drive.

References


