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SIMPLE DYNAMIC ENERGY EFFICIENT FIELD ORIENTED CONTROL IN INDUCTION MOTORS

Grygorii Diachenko, Gernot Schullerus*
National Mining University, Dnipropetrovsk, Ukraine
* Reutlingen University, School of Engineering, Reutlingen, Germany

Abstract: *The current paper discusses the optimal choice of a filter time constant for filtering the steady state flux reference in an energy efficient control strategy for changing load torques. It is shown that by appropriately choosing the filter time constant as a fraction of the rotor time constant the instantaneous power losses after a load torque step can be significantly reduced compared to the standard case. The analysis for the appropriate choice of the filter time constant is based on a numerical study for three different induction motors with different rated powers.*

Key Words: ***energy efficiency, field-oriented control, power losses, filtering, dynamic operation***

1. INTRODUCTION

The demand for induction motors has been continuously increasing during the last decades in a variety of applications due to its robustness and low cost compared to permanent magnet synchronous machines. One of the various methods used for controlling the induction motor's magnetic flux and speed in such systems is Field-Oriented Control (FOC), which was introduced by F. Blaschke in 1971 [1] and is state-of-the-art nowadays for electrical drives. However, in part load operation the efficiency of the induction motor dramatically decreases if the magnetic flux is kept at the nominal level throughout the entire load range. It leads to over-excitation and redundant copper losses for the case when the machine is in part-loaded mode of operation. Thus, the minimization of losses has gained importance in cases when a motor drive has to operate in a wider load range. The reduction of the electrical energy consumed by induction motors is particularly interesting in applications like conveyors and with a segment of the consumer market called HVAC, that is, Heating, Ventilation and Air-Condition. These applications consume a large part of the total energy consumed by induction motors. To reduce the power losses and thus increase the efficiency of the motor in such applications an abundant number of different energy efficient control strategies have been developed as described in [2-5] and the references cited therein. The focus of these methods is on the minimization of the power losses when the machine is operated in a steady state at a given speed and a given torque.

However, only a comparatively small number of publications discuss the minimization of power losses in dynamic operation mode due to a changing motor torque. An offline numerical solution based on a priori known speed and torque trajectories is described in [6]. This experimental study has shown that the method provides a significant reduction of power losses compared to the operation under nominal magnetizing current. However, the necessity of offline pre-calculation of the optimal trajectories restricts the application domain. An approach where the optimal trajectory is computed online based on an online optimization is introduced in [10]. In [7] a method for determining the loss-minimizing flux linkage reference based on the corresponding steady-state loss function both for steady-state and dynamic operation is presented. However, as will be shown in this paper, in such an approach the flux linkage reference must be filtered in order to avoid high magnetization current levels during flux transients. Although such a filter is used in [7] the appropriate choice of the filter time constant has not been discussed.

This paper addresses this point and investigates in a numerical study an optimal choice for the filter time constant for filtering the flux linkage reference. The study is done with three different motors with different rated powers. The objective of the analysis is to determine the filter time constant as a fraction of the rotor time constant of the motor to give the user a simple design criterion.

This paper is organized as follows. First, a brief review of the basic notions used in this paper will be given in section 2. Section 3 describes the main idea based on the problem analysis resulting in a method to obtain a simple and easy implementable solution. A numerical study is given in section 4. Simulation results using the proposed strategy are presented in section 5, and the conclusions are given in section 6.

2. PRELIMINARIES

For the mathematical modelling of the induction motor all variables are transformed from the three-phase system to an orthogonal amplitude invariant dq reference frame with a direct (d) and a quadrature (q) axis. Details regarding reference frame theory can be found in the relevant literature source [9].

2.1. Motor model

We will use in the sequel the model parameters of the Γ-inverse equivalent circuit of an induction motor (IM) given in Figure 1.

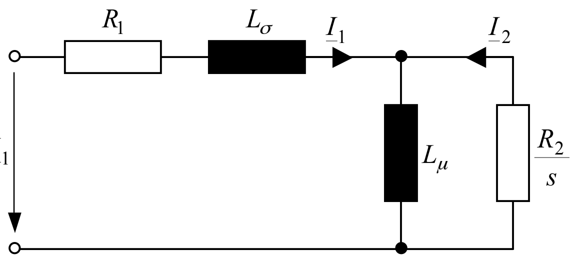

Fig. 1. *Γ-inverse equivalent circuit of IM*

Assume that the speed and current regulators of field-oriented control have high enough performance to ensure the control characteristic close to perfectly rigid, that is, the dynamics of the stator currents is significantly higher than the dynamics of the magnetic flux and speed. In other words, a stepwise change in the load on the motor shaft does not lead to a significant deviation of the speed from its reference. In such a case, the dynamics of the speed and current controllers can be disregarded. The reduced motor model can be written as follows:

$$\dot{\psi}_2 = -\frac{R_2}{L_\mu}\psi_2 + R_2 I_{1d}, \qquad M_M = \frac{3}{2} Z_p \psi_2 I_{1q}. \tag{1}$$

2.2. Power loss and optimal mode

Directly from the physical interpretation of the equivalent circuit the copper losses are given by the following expression:

$$P_V = \frac{3}{2} R_1 I_1^2 + \frac{3}{2} R_2 I_2^2. \tag{2}$$

The total values of the currents in the rotating dq coordinate system are calculated by Pythagoras' Theorem:

$$I_1 = \sqrt{I_{1d}^2 + I_{1q}^2}, I_2 = \sqrt{I_{2d}^2 + I_{2q}^2}. \tag{3}$$

According to the equations of the magnetic system of the motor, in field oriented control we have

$$I_{2d} = -I_{1d} + \frac{1}{L_\mu}\psi_2, I_{2q} = -I_{1q}. \tag{4}$$

Now (3) and (4) can be substituted in (2) resulting in:

$$P_V = \frac{3}{2}(R_1 + R_2) I_{1d}^2 + \frac{3}{2}(R_1 + R_2) I_{1q}^2 + \frac{3}{2}\frac{R_2}{L_\mu^2}\psi_2^2 - 3\frac{R_2}{L_\mu}\psi_2 I_{1d}. \tag{5}$$

Thus, the optimal control problem consists in the minimization of the time integral of power losses, that is, the energy loss

$$J = \int_0^T \Big(\frac{3}{2}(R_1 + R_2) I_{1d}^2 + \frac{3}{2}(R_1 + R_2) I_{1q}^2 + \frac{3}{2}\frac{R_2}{L_\mu^2}\psi_2^2 - 3\frac{R_2}{L_\mu}\psi_2 I_{1d} \Big) dt, \tag{6}$$

where T is the transient period.

Using a steady-state value of the rotor magnetic flux $\psi_2 = L_\mu I_{1d}$, after certain mathematical simplifications of (5), we obtain the expression for the power losses in steady-state mode:

$$P_{V,stationary} = \frac{3}{2} R_1 I_{1d}^2 + \frac{3}{2}(R_1 + R_2) I_{1q}^2. \tag{7}$$

In steady-state the optimal rotor flux linkage value is given by

$$\psi_{2,stationary} = \sqrt{\frac{2}{3}\frac{M_M L_\mu}{Z_p}\sqrt{\frac{R_1 + R_2}{R_1}}} \tag{8}$$

In the solution of the optimization problem based on the performance measure (6) in the case of a load torque step the boundary conditions $\psi_2(0) = \psi_{2,stationary}(M_M)$ and $\psi_2(T) = \psi_{2,stationary}(M_M + \Delta M_M)$ can be determined using (8).

3. MAIN IDEA

3.1. Analysis

Assume that before a perturbation in the motor torque of magnitude ΔM_M the motor operates in optimal mode of power consumption. It is obvious that after a step change in the torque M_M on the shaft to the new value $M_M + \Delta M_M$, $\Delta M_M \geq 0$, the speed regulator will increase the reference of quadrature current I_{1q} in order to maintain the speed at a given level. Consider two boundary modes of behavior of the system under a step change in the load torque on the motor shaft illustrated in Figure 2:

1. The magnetic flux linkage ψ_2 stays unvaried.
2. The magnetic flux linkage ψ_2 is set to its new optimum value for the new load level.

In the first case, I_{1q} rapidly increases to its steady state value, but under the new value of the torque on the shaft the power consumption will not be optimal. In the second case, if we consider the peak value of the power losses during the transient period T in Figure 2 its value will be much greater than in case 1 because with the step increase in the magnetic flux linkage reference $\psi_{2,ref}$, a rapid change in current I_{1d} is observed. That is, the peak power loss is much lower in case 1. As illustrated in Figure 2 this peak in the power losses can be significantly decreased by filtering the flux reference value using an appropriately chosen filter time constant. This will be discussed in the following section.

3.2. Method

The main idea of this paper is to decrease the instantaneous power loss overshoot during a load torque step by applying a first-order filtering with respect to the input signal of the rotor flux linkage regulator given in Figure 3. In order to give the user an easy to apply design criterion the filter time constant is given as a fraction of the rotor time constant of the considered motor.

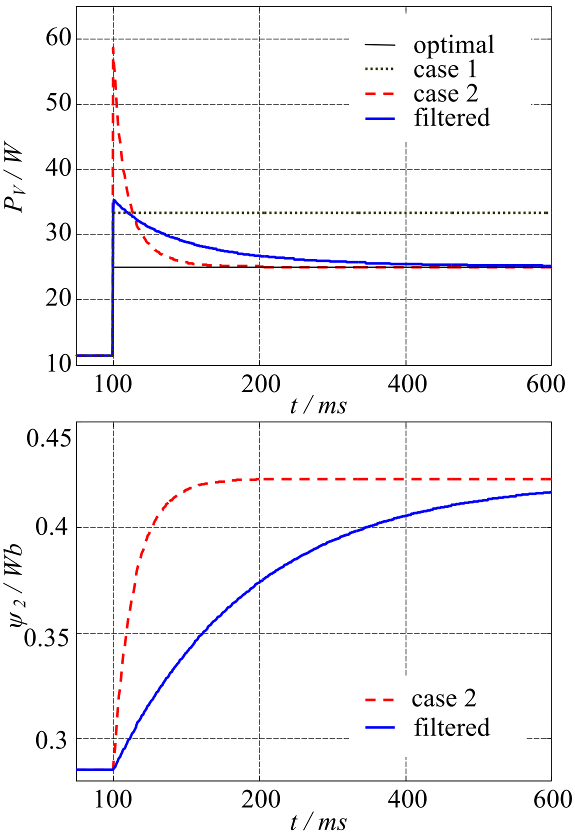

Fig. 2. *Power losses P_V and flux linkage ψ_2 during load step change*

Denote $T_\psi = kT_2$ as the filter time constant. T_2 is the rotor time constant and k is a multiplier.

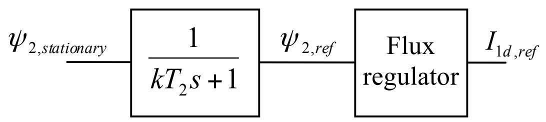

Fig. 3. *Filtering*

As illustrated in Figure 2 this approach reduces the peak power loss under a step change in load torque on the shaft of the motor and it converges to the optimal value. Thus, the problem is reduced to finding the optimal value of the multiplier k, such that the integral of energy losses J in (6) tends to its minimum.

4. NUMERICAL STUDY

Let us consider the impact of first-order filtering. To simplify the calculations we will assume in the sequel that the flux regulator is fast enough such that the flux linkage follows its reference closely. In this case we can assume for the flux linkage dynamics the following equation:

$$\dot{\psi}_2(t) = -\frac{1}{T_\psi}\psi_2 + \frac{1}{T_\psi}\psi_{2,stationary}. \qquad (9)$$

The solution of this differential equation is given by

$$\psi_2(t) = \psi(0)e^{-\frac{t}{T_\psi}} + \psi_{2,stationary}\left(1 - e^{-\frac{t}{T_\psi}}\right). \qquad (10)$$

The magnetizing current and the quadrature current given a certain flux linkage trajectory and a load torque step can be computed by rewriting (1) from

$$I_{1d} = \frac{1}{R_2}\left(\dot{\psi}_2 + R_2\frac{\psi_2}{L_\mu}\right), \quad I_{1q} = \frac{2(M + \Delta M)}{3Z_P\psi_2}. \qquad (11)$$

Now (9), (10) and (11) can be substituted in (6) resulting in an expression of the integral that depends on the time interval T and the multiplier k.

Numerical investigations were conducted using parameters of induction motors with rated powers of 370W, 4kW and 11kW. The nameplate data for these motors is given in the appendix. The main inductance is assumed to be constant.

The first test was performed for different load steps with increasing load from 25 % up to 100 % of nominal motor torque M_N. The obtained trajectories of the loss energy W_{V1} as a function of k are presented in Figure 4.

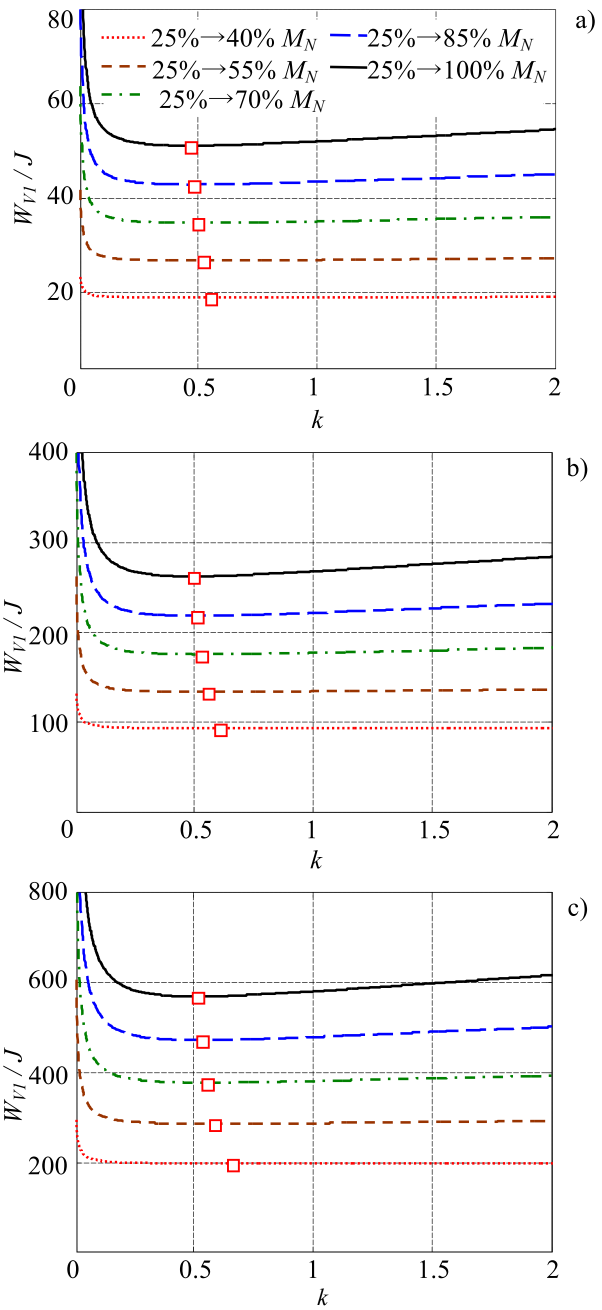

Fig. 4. *Calculated trajectories of loss energy W_{V1} for load step increase for: a) 370W-motor; b) 4kW-motor; c) 11kW-motor*

The duration of the transients were chosen as follows: for the 370W-motor – 0.4 sec, for the 4kW-motor – 0.9 sec and for the 11kW-motor – 1.4 sec.

The second test was done for different load steps with decreasing load from 100 % and below to 25 % of the nominal motor torque. The results for the loss energy W_{V2} are given in Figure 5.

Directly from Figure 4 it can be seen that as the rated power of the motor increases the optimal value for k increases slightly as well. Numerical investigations shown in Figure 5 give almost the same result for the multiplier k with the motor rated power increase. In both cases an appropriate choice of the multiplier k is $k \in [0.5\ 1]$.

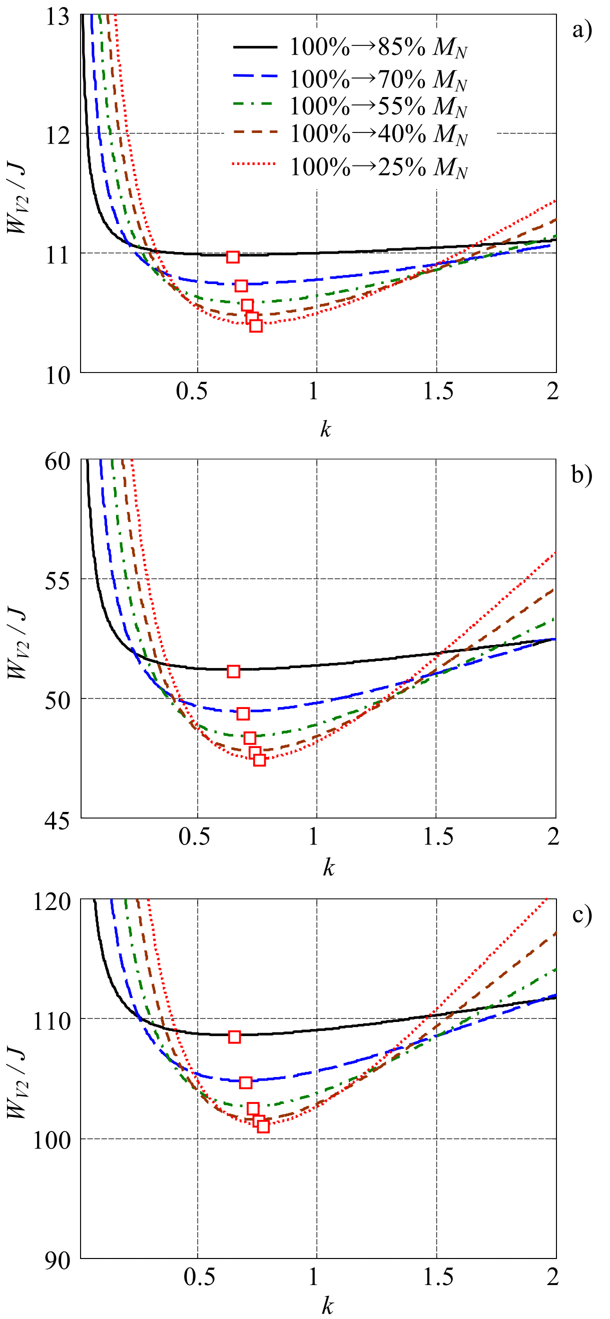

Fig. 5. *Calculated trajectories of loss energy W_{V2} for load step decrease for: a) 370W- motor; b) 4kW- motor; c) 11kW- motor*

5. SIMULATION

For the verification of the proposed strategy a simulation was implemented in a MATLAB/Simulink environment. For the simulation the parameters of the 370W induction motor were used. The optimal filter time constant is chosen equal to 0.45 of the rotor time constant T_2. Simulation results for the power losses P_V, energy losses W_V and the magnetizing current I_{1d} for the proposed strategy for the control of the rotor flux linkage ψ_2 are illustrated in Figure 6 for a load step from 25 % to 100 % of nominal motor torque in the time interval $t \in [0\ 200]$ms and from 100 % to 25 % of the nominal motor torque in the time interval $t \in [200\ 400]$ ms.

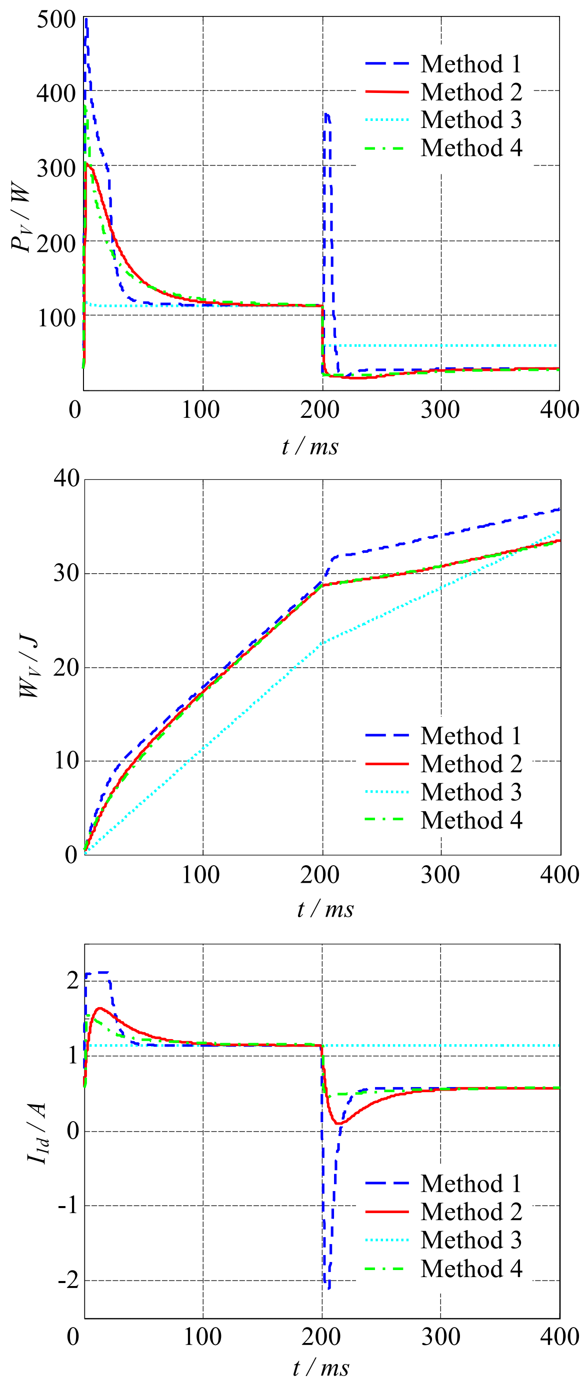

Fig. 6. *Simulation results*

The simulations show a comparison between the following methods:

- Method 1 step wise reference for flux,
- Method 2 filtered reference signal,
- Method 3 constant reference for magnetic flux when load is 100% and
- Method 4 optimal trajectory computed with a model predictive approach based using the toolbox from [8].

The simulations illustrate the improvement due to the filtering with respect to the unfiltered case. Although the resulting trajectory is not optimal, the difference to the optimal trajectory obtained with Method 4 is acceptable.

6. CONCLUSION

A loss-minimizing flux control method based on filtering the rotor flux linkage reference for the flux regulator has been proposed in this paper. The main idea is to determine an appropriate filter time constant as a fraction of the rotor time constant using a multiplier k. The result of a numerical study shows that the optimal value of the multiplier k is in a range between 0.5 and 1. This solution is simple to implement and can be easily integrated in existing inverters. Simulation results have shown that the proposed approach to the energy efficiency optimization problem for motor torque steps leads to a reduction of power losses during transients compared to a conventional approach. In addition, the obtained trajectories are very close to the ones obtained with a MPC approach.

7. APPENDIX

Parameters of three different motors have been used. The Nameplate data for these motors are given in Table 1.

Table 1. Nameplate data

Motor 1					
Rated power	370	W	Rated current	1.08	A
Rated torque	2.6	Nm	Rated speed	1380	rpm
Mom. of inertia	$4.94 \cdot 10^{-4}$	kgm^2	Pole pairs	2	
Motor 2					
Rated power	4	kW	Rated current	8.1	A
Rated torque	26.6	Nm	Rated speed	1435	rpm
Mom. of inertia	$146 \cdot 10^{-4}$	kgm^2	Pole pairs	2	
Motor 3					
Rated power	11	kW	Rated current	22	A
Rated torque	71.9	Nm	Rated speed	1480	rpm
Mom. of inertia	$180 \cdot 10^{-4}$	kgm^2	Pole pairs	2	

Motor 1 has been used for calculations and simulations. Motors 2 and 3 have been investigated solely in calculations.

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