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Optimization of the control of a doubly fed induction machine

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Abstract—This paper focuses on finding an optimal control for a doubly fed induction machine (DFIM) in motor mode. Our purpose is not to improve the quality of the DFIM functioning but to find a method to improve it. Thus we will start with a fixed system made by a DFIM and two ideal 3 phases voltage inverter with an open loop static V/f control. A method will demonstrate its efficiency to improve that control for the copper loss.

This method is based on direct shooting techniques associated with a MATLAB optimization solver: *fmincon*.

Keywords—Doubly fed induction machine (DFIM); ideal 3 phases voltage inverter; open loop static V/f control; copper loss; direct shooting method; optimization; energetic efficiency

I. INTRODUCTION

The Doubly Fed Induction Machine (DFIM) is often used as a Doubly Fed Induction Generator (DFIG). That is why, works are done to optimize the DFIG functioning as in [1] and [2]. Control of DFIM has been developed in [3], but now the goal is to find a method to optimize it, for example versus the copper loss.

In this paper, a presentation of the studied system, (a DFIM in motor mode fed by two ideal voltage inverters with an open loop static V/f control), will be made. A very simple DFIM open loop control is chosen to point the optimization aspect to reduce the copper loss. Thus, a model of this system will be given. With this model, the direct shooting method will be developed and used. Finally the results will be simulated to compare them with a traditional ramp control.

The system is presented in Section II and its model is described in Section III. The optimization problem and methods are shown in Section IV. And finally, in section V the numerical results so obtained are validated with SABER© software.

II. SYSTEM PRESENTATION

The system is composed as in Fig. 1:

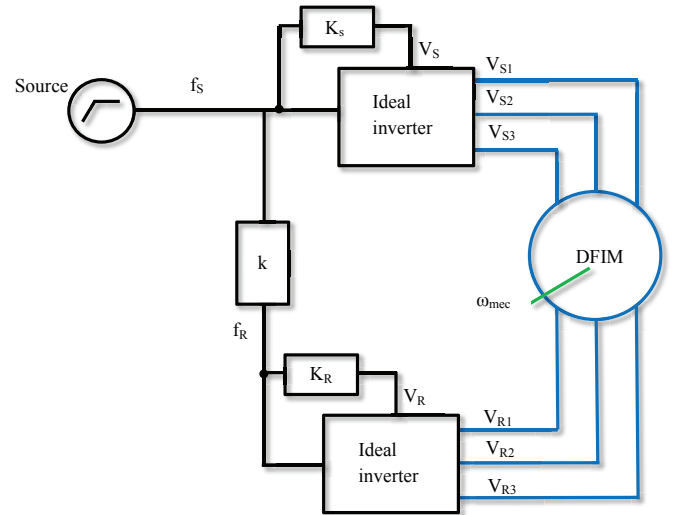


Fig. 1. General schema of DFIM drive controlled by static V/f.

K_s = static V/f constant for the stator side,

K_r = static V/f constant for the rotor side.

The source gives a continuous signal $f_s(t)$ which is the control of this DFIM. With this signal, $f_r(t)$ is calculated. Those signals represent the electrical variable frequencies of the stator and the rotor respectively. The corresponding value of the supply tension of the DFIM is calculated with them. For those transformations, ideal 3 phases voltage inverters are used. They have as inputs, a frequency and an amplitude and give an equilibrated tension system at the end to feed the DFIM.

The aim is to try to optimize the stator frequency signal $f_s(t)$.

III. MODELING

In this part, the model used in the optimization method is described. The static converter model is not used at the beginning because the goal is to reduce the copper loss in the motor. It makes a simplified model, to focus on the DFIM, as it is the real purpose.

A. DFIM Model

The DFIM model used in this paper is developed in François Bonnet's PhD thesis [4].

The expression of the control $u(t)$ is put in the expressions of frequencies:

$$f_s(t) = k \times u(t) \times t \quad \text{and} \quad f_r(t) = u(t) \times t, \quad (1)$$

with:

$f_s(t)$ - electrical values frequencies of the stator,

$f_r(t)$ - electrical values frequencies of the rotor,

$u(t)$ - system control variable,

k - frequency repartition coefficient between rotor and stator.

This formulation is used to avoid frequency step.

Now, according to the used control (static V/f law) the effective (rms) values of tensions are:

$$V_S(t) = f_S(t) \times 2\pi \times \Phi_{SN} \quad (2)$$

$$\text{and } V_R(t) = f_R(t) \times 2\pi \times \Phi_{RN} \quad (3)$$

with:

Φ_{SN} - nominal stator flux,

Φ_{RN} - nominal rotor flux,

$V_S(t)$ - effective value of the stator tension,

$V_R(t)$ - effective value of the rotor tension.

These equations are transformed to a static frame (Concordia basis) [5] to express the tension system with the flux:

$$\begin{bmatrix} V_{Sa} \\ V_{S\beta} \\ V_{Ra} \\ V_{R\beta} \end{bmatrix} = \mathbf{R}_{\text{mat}} \mathbf{L}_{\text{mat}}^{-1} \begin{bmatrix} \Phi_{Sa} \\ \Phi_{S\beta} \\ \Phi_{Ra} \\ \Phi_{R\beta} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{Sa} \\ \Phi_{S\beta} \\ \Phi_{Ra} \\ \Phi_{R\beta} \end{bmatrix}, \quad (4)$$

with:

$$\mathbf{R}_{\text{mat}} = \begin{bmatrix} \mathbf{R}_{SS} & 0 \\ 0 & \mathbf{R}_{RR} \end{bmatrix},$$

$$\mathbf{R}_{SS} = \begin{bmatrix} R_S & 0 \\ 0 & R_S \end{bmatrix}, \quad \mathbf{R}_{RR} = \begin{bmatrix} R_R & 0 \\ 0 & R_R \end{bmatrix}$$

$$\mathbf{L}_{\text{mat}} = \begin{bmatrix} L_S & 0 & M \cos \theta & -M \sin \theta \\ 0 & L_S & M \sin \theta & M \cos \theta \\ M \cos \theta & M \sin \theta & L_R & 0 \\ -M \sin \theta & M \cos \theta & 0 & L_R \end{bmatrix}.$$

And finally, the expression of the currents with the flux is:

$$\begin{bmatrix} I_{Sa} \\ I_{S\beta} \\ I_{Ra} \\ I_{R\beta} \end{bmatrix} = \mathbf{L}_{\text{mat}}^{-1} \begin{bmatrix} \Phi_{Sa} \\ \Phi_{S\beta} \\ \Phi_{Ra} \\ \Phi_{R\beta} \end{bmatrix}, \quad (5)$$

with:

L_S, L_R - cyclic stator, rotor inductance,

M the cyclic mutual inductance between the stator and the rotor,

R_S, R_R - stator rotor resistance,

$I_{Sa}, I_{S\beta}$ - stator currents in the α, β axes,

$I_{Ra}, I_{R\beta}$ - rotor currents in the α, β axes,

$V_{Sa}, V_{S\beta}$ - stator voltage in the α, β axes,

$V_{Ra}, V_{R\beta}$ - rotor voltage in the α, β axes,

$\phi_{Sa}, \phi_{S\beta}$ - stator flux in the axis α, β axes,

$\phi_{Ra}, \phi_{R\beta}$ - rotor flux in the axis α, β axes.

Rotor electrical position and speed can be defined as follows:

$$\theta = \frac{d\omega}{dt} \quad \text{and} \quad \omega = 2\pi(f_S(t) - f_R(t)).$$

B. Toward an optimization formulation

The model equations are put in a suitable form for optimization. A state representation is given by:

$$\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}(u) \quad (6)$$

where:

$$\text{State vector matrix: } \mathbf{X} = \begin{bmatrix} I_{Sa} \\ I_{S\beta} \\ I_{Ra} \\ I_{R\beta} \end{bmatrix}.$$

$$\text{Dynamic system matrix: } \mathbf{A} = \mathbf{R}_{\text{mat}} \mathbf{L}_{\text{mat}}^{-1}.$$

$$\text{Control matrix: } \mathbf{B}(u) = \mathbf{L}_{\text{mat}}^{-1} \begin{bmatrix} V_{S\alpha} \\ V_{S\beta} \\ V_{R\alpha} \\ V_{R\beta} \end{bmatrix}.$$

IV. OPTIMIZATION PROBLEM

We introduce the mode separation principle. In this case, the temporal derivative of θ is considered as null because the electrical variables evolve faster than the mechanic ones.

The main point developed here is to find a solution to minimize the copper loss, so the cost function will be:

$$E_J(u) = \int_0^{t_f} 3R_S(I_{S\alpha}^2 + I_{S\beta}^2) + 3R_R(I_{R\alpha}^2 + I_{R\beta}^2) dt \quad (7)$$

Following the state equation (7), with an time horizon $t_f = 3$ seconds, the physical constraints are defined by:

- $0 < I_{Si} < I_{Sn}$ Stator current limitation to nominal values,
- $0 < I_{Ri} < I_{Rn}$ Rotor current limitation to nominal values,
- $0 < V_{Si} < 230$ V Stator voltage limitation to nominal values,
- $0 < V_{Ri} < 130$ V Rotor voltage limitation to nominal values,
- $0 < \omega = 2\pi(f_S - f_R) < 188$ rad/s Speed limitation.

At $t = 3$ s the final rotation speed must be reached:

$$\Omega = \Omega_{\text{final}} = 188 \text{ rad/s Final speed.}$$

A. Indirect shooting method

First Pontryagin Max Principle [6] was investigated but the Hamiltonian of the system is too complex to yield a differential system of equations which could be efficiently numerically solved.

To illustrate, here is the Hamiltonian:

$$\begin{aligned} H = & -\left(3R_S(I_{S\alpha}^2 + I_{S\beta}^2) + 3R_R(I_{R\alpha}^2 + I_{R\beta}^2)\right) \\ & + \frac{1}{\mathcal{M}^2 - \mathcal{L}_S \mathcal{L}_R} \left(z_1 (-\mathcal{L}_R R_S I_{S\alpha} + R_R \mathcal{M} I_{R\alpha} \cos \theta - R_R \mathcal{M} I_{R\beta} \sin \theta \right. \\ & - \mathcal{L}_R k \phi_{Sn} 2\pi\sqrt{3}ut \sin(k2\pi ut^2) + \mathcal{M} \cos \theta \phi_{Rn} 2\pi\sqrt{3}ut \sin(2\pi ut^2) \\ & - \mathcal{M} \sin \theta \phi_{Rn} 2\pi\sqrt{3}ut \cos(2\pi ut^2)) \\ & + z_2 (-\mathcal{L}_R R_S I_{S\beta} + R_R \mathcal{M} I_{R\beta} \cos \theta + R_R \mathcal{M} I_{R\alpha} \sin \theta - \mathcal{L}_R k \phi_{Sn} 2\pi\sqrt{3}ut \cos(k2\pi ut^2) \\ & + \mathcal{M} \sin \theta \phi_{Rn} 2\pi\sqrt{3}ut \sin(2\pi ut^2) + \mathcal{M} \cos \theta \phi_{Rn} 2\pi\sqrt{3}ut \cos(2\pi ut^2)) \\ & + z_3 (-\mathcal{L}_S R_R I_{R\alpha} + R_S \mathcal{M} I_{S\alpha} \cos \theta + R_S \mathcal{M} I_{S\beta} \sin \theta - \mathcal{L}_S \phi_{Rn} 2\pi\sqrt{3}ut \sin(2\pi ut^2) \\ & + \mathcal{M} \cos \theta k \phi_{Sn} 2\pi\sqrt{3}ut \sin(k2\pi ut^2) + \mathcal{M} \sin \theta k \phi_{Sn} 2\pi\sqrt{3}ut \cos(k2\pi ut^2)) \\ & + z_4 (-\mathcal{L}_S R_R I_{R\beta} + R_S \mathcal{M} I_{S\beta} \cos \theta - R_S \mathcal{M} I_{S\alpha} \sin \theta - \mathcal{L}_S \phi_{Rn} 2\pi\sqrt{3}ut \cos(2\pi ut^2) \\ & - \mathcal{M} \sin \theta k \phi_{Sn} 2\pi\sqrt{3}ut \sin(k2\pi ut^2) + \mathcal{M} \cos \theta k \phi_{Sn} 2\pi\sqrt{3}ut \cos(k2\pi ut^2)) \end{aligned}$$

Because of the complexity of the Hamiltonian the optimal control is difficult to find.

B. Direct shooting method

Secondly the direct shooting method [7] is used. This method is based on the discretion of the time by small steps h . Hence, this yields to solve a large scale static optimization problem:

$$\min_{u^i \in \mathbb{R}^N} \sum_0^N X^{i+1} = X^i + h(A X^i + B(u^i)) \quad (8)$$

with the same constraints than previously.

For solving this large scale optimization problem the *fmincon* function of MATLAB is used to optimize a vector of N points representing the values of the control $u(t)$ at each step of the discretized time. As a result, a vector of N points is given by the routine and at the end it will correspond to the optimal control for the system.

As the final electrical frequency is about 26 Hz the time step must be small. That is why this is a large scale optimization problem. To begin a small amount of point is used with a small temporal horizon with always a small time step. Then after checking the results we enlarge the time horizon as well as the number of point to obtain the final optimization.

Numerical solutions are reported in Fig. 2, 3, 4 and 5 for $N=500$. Those results must be checked by comparing them with a simulation tool.

V. VALIDATION OF THE OPTIMAL SOLUTION

In order to validate this optimization method SABER© software is used. The same schema than in presentation (Fig. 1) is used twice. One way to simulate the regular ramp control, and the other way to simulate the optimized control.

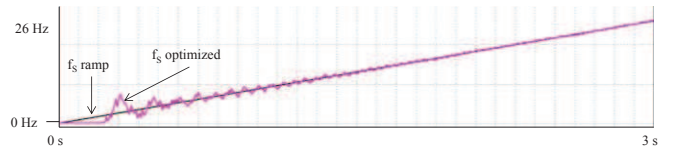


Fig. 2. Control sources for the systems.

The control is shown in the Fig. 2. In black, the regular control input and in pink the optimized control input. These signals are given as sources in the system.

The outputs of these control signals, i.e., the rotation speed, have the shape as showed in Fig. 3:

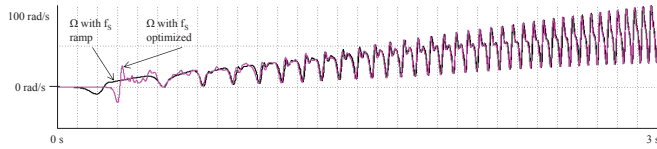


Fig. 3. Systems responses (rotation speed).

The response is shown in Fig. 3. In black, the response with the regular ramp control, and in pink the response with the optimized one. These signals are given as sources in the system.

As said at the beginning, the quality of the torque or the rotation speed is not the aim, what is important is that at the end, with the two different controls, the DFIM has the same behavior.

Now, the main result:

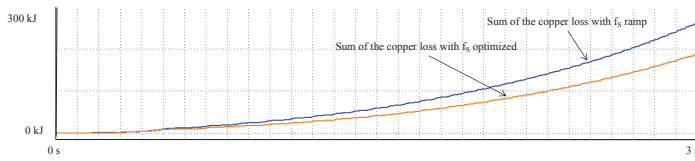


Fig. 4. Copper loss sum E_J (7).

As shown in Fig. 4, the sum of the copper loss is lowered by 28% in the case of an optimized control.

Electrical quantities can also be shown:

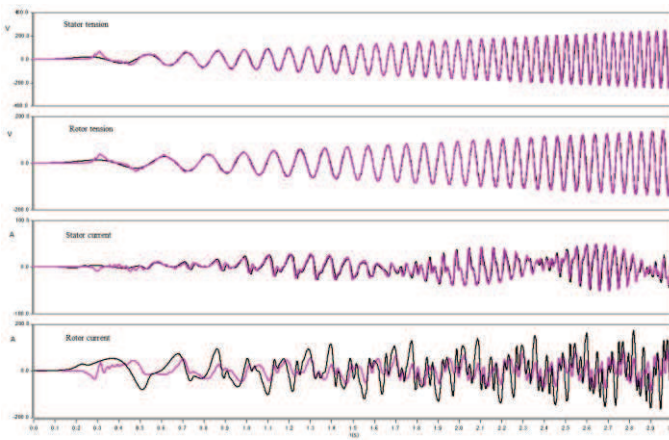


Fig. 5. In pink, the “optimized” electrical quantities and in black, the other one.

In Fig 5 the electrical quantities appears similar in both case except for the rotor current which is lower in the optimized case.

In many industrial applications, the power system architecture is given. And one way to improve the system performances can be through the control strategy.

In this paper, the authors present the direct shooting method to optimize efficiently the behavior of a DFIM speed drive. This optimization concept allows us to adapt the control strategy to the required operation of the system taking into account the formulated constraints.

The optimization process is very difficult in real time. Consequently, a very simple control method, V/f law, was chosen to validate the optimization method applied in deferred time.

To calculate this direct shooting method, we have to choose the control input, to place it in the system model and to define the cost function to be optimized. The main problem is the compromise between the time scale and the number of points to represent clearly and precisely the principle variables of the studied system.

In the next step of this study, the cost function can be completed with iron loss or torque quality for example, and the control can be switched to a more complex one such as the non linear Double Direct Torque Control (DDTC) or the linear Field Oriented Control (FOC). The model of two real voltage inverters (one for the stator side and one for the rotor side) can be added too. The cost function could be eventually completed with the losses of them.

In future works, the global optimization aspect will be considered to associate different real time controls to the DFIM system to improve their performances.

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