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Research article

Real time PI-backstepping induction machine drive with efficiency optimization

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ABSTRACT

This paper describes a robust and efficient speed control of a three phase induction machine (IM) subjected to load disturbances. First, a Multiple-Input Multiple-Output (MIMO) PI-Backstepping controller is proposed for a robust and highly accurate tracking of the mechanical speed and rotor flux. Asymptotic stability of the control scheme is proven by Lyapunov Stability Theory. Second, an active online optimization algorithm is used to optimize the efficiency of the drive system. The efficiency improvement approach consists of adjusting the rotor flux with respect to the load torque in order to minimize total losses in the IM. A dSPACE DS1104 R&D board is used to implement the proposed solution. The experimental results released on 3 *kW* squirrel cage IM, show that the reference speed as well as the rotor flux are rapidly achieved with a fast transient response and without overshoot. A good load disturbances rejection response and IM parameters variation are fairly handled. The improvement of drive system efficiency reaches up to 180% at light load.

1. Introduction

The economic reasons and environmental friendliness are taken into primary consideration in the design of electric drive systems. Almost all of IMs drive strategies, based on the Field Oriented Control (FOC) introduced initially by Blaschke in 1972. This control technique considers that the magnetic flux reference is constant and closes to its rated level (λ_{rnm}) [1,2] for high dynamic performance regardless of the operating points. Such procedure results in an unsatisfactory energy efficiency when the IM is under-loaded [3]. Many investigations have shown that almost 45% of IMs drive 40% of their rated load [4]. To overcome this drawback, the flux must be auto-adjusted online in respect of the load torque to achieve a minimum power loss [5,6]. In fact, the efficiency optimization algorithm tracks the unique optimal flux leakage value for each operating point and apply it to controlled IM. In the literature, many approaches are proposed to optimize the drive system efficiency [4–10], these solutions are basically divided into two categories: Model Based Optimization (MBO) and Search Algorithm based Optimization (SAO). Main drawbacks of the MBO are the number of arithmetic operations involved in the solution of the loss model and its high sensitivity to parameters variations [11]. The SAO are characterized by their parameter insensitivity. However, it has some serious disadvantages such as a high torque ripples [10] and very slow convergence to optimal operating point compared to MBO. In these cases, the search space is very large and results in a more time to seeking the optimal operating conditions. The combination of this two methods is so called Hybrid Algorithm based Optimization (HAO) which tries to get benefit from their advantages. A complete overview of existing optimization methods is found in [7].

Based on a mathematical model of IM, the MBO can rapidly converge to the optimal flux. J. Rivera et al. propose on their work [9] a loss model based on the resistive and core loss under the assumption that all IM parameters are invariant and the core loss can be emulated by a constant resistance. However, on the one hand, the stator and rotor resistances may vary up 50% and 100% respectively [12]. On the other hand, the core-loss considerably depends on the flux level, stator frequency and inverter switching frequency in practices [6,13]. Indeed, without a real-time parameters adaptation mechanisms, the optimization algorithm can underestimate the optimal flux, can also lead to destabilize the drive system and cause the “motor stalling” issue specially in presence of sudden change in load torque. Even with IM parameters tracking algorithms, it is very difficult to identify the IM parameters simultaneously and accurately in the full operating region [14]. To overcome the parameters variation problems and its impact on the stability of the drive system, this paper proposes a cooperative two-step efficiency optimization. Firstly, by using a simplified model losses, the controller quickly achieves a first

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Nomenclature

v_{sd}, v_{sq}	: d and q components of stator voltages;
i_{sd}, i_{sq}	: d and q components of stator currents;
λ_{rd}, λ_{rq}	: d and q components of rotor flux;
C_e, C_r	: Electromagnetic and load torques;
P_{topt}, P_{tot}	: Optimal and total power losses;
η, η_0, η_{opt}	: Actual, rated and optimal yields;
L_s, L_r, M	: Stator, rotor and mutual inductances;
R_s, R_r	: Stator and rotor resistances;
p	: Number of pole pairs;
J	: The inertia of IM and load;
ω_r, ω_s	: Rotor and rotating frame angular velocity;
$\sigma = 1 - \frac{M^2}{L_r L_s}$	: Total linkage coefficient.

approximation of optimal flux and so called "suboptimal flux". This step, reduces the possible solutions space without disestablishing the drive system. Concerning the second step, from the near-optimal operating point, a search algorithm achieves a smooth and robust convergence to the optimal flux.

As mentioned early, the efficiency optimization consists of decreasing the flux leakage value in the IM to its acceptable minimum level. As a matter of fact, the success of the efficiency optimization highly depends on the accuracy and the robustness of the flux regulation. Indeed, accurate estimation and robust flux controller guarantees the maximization of the energy saving. In addition, it avoids the motor stalling caused by low flux level. In this respective, the paper refers to Direct Field Oriented Control (DFOC) scheme to track the flux reference generated by the hybrid optimization algorithm. Recently, various control schemes have been proposed and tested in different control loops of DFOC, such as, Backstepping [15], sliding mode [9,16–20], feedback linearization [21–23], LPV approach [24]. However, conventional proportional/integral (PI) regulators still commonly used in industry due to its simplicity and ease of implementation [25]. Nevertheless, without parameters adaptation, the desired performances response (i.e accuracy, response times, smooth running…) are not obtained, especially in presence of sudden change in load torque and external disturbances [26]. To overcome its sensitivity to parameters variation, an online parameter tracking algorithm is used to estimate the corresponding parameters in the FOC [27]. However, this solution increases the complexity of the controller and the difficulty of a real-time implementation. Based on the scheme proposed by Benzineb et al [28] in stationary reference frame, this paper retains the conventional PI correctors and combines it with a Backstepping stage in rotating reference frame. This approach aims to benefit of simplicity of PI controller and the robustness of the Backstepping technique. Indeed, the PI controller achieves a high accuracy tracking of direct and quadrature currents references. Backstepping stage simultaneously guarantees, on the one hand a perfect tracking of rotor speed and flux references, and the decoupling between their dynamic on other hand. The stability of proposed controller is proven by Lyapunov Stability Theory.

2. Model of IM in oriented (*d*, *q*) reference frame

The FOC theory achieves the decoupling between flux and torque dynamics. This technique involves aligning the controlled flux space vector with d-axis of the rotating reference frame $\left(\vec{\lambda}_r = \vec{\lambda}_{rd}\right)$. In fact, the nonlinear state equation of IM can be written by the following equation:

$$\begin{cases} \frac{di_{Ld}}{dt} = f_{id}\left(i_{Ld}, i_{Lq}, \lambda_r, \omega_r\right) + h_d(v_{sd}) \\ \frac{di_{Lq}}{dt} = f_{iq}\left(i_{Ld}, i_{Lq}, \lambda_r, \omega_r\right) + h_q\left(v_{sq}\right) \\ \frac{d\lambda_r}{dt} = f_\lambda\left(i_{Ld}, \lambda_r\right) = M\frac{R_r}{L_r}i_{Ld} - \frac{R_r}{L_r}\lambda_r \\ \frac{d\omega_r}{dt} = f_\omega\left(i_{Lq}, \lambda_r, \omega_r, C_r\right) = \frac{pM}{JL_r}\lambda_r i_{Lq} - \frac{C_r - f\omega_r}{J} \end{cases} \tag{1}$$

with

$$\begin{cases} f_{id}\left(i_{Ld}, i_{Lq}, \lambda_r, \omega_r\right) = -\left(\frac{1-\sigma}{\sigma}\frac{R_r}{L_r} + \frac{1}{\sigma L_s}R_{sc}\right)i_{Ld} \\ +p\omega_r i_{Lq} + \frac{R_r}{\varepsilon L_r}\lambda_{rd} + \frac{R_r}{L_r}M\frac{i_{Lq}^2}{\lambda_{rd}} \\ f_{iq}\left(i_{Ld}, i_{Lq}, \lambda_r, \omega_r\right) = -\left(\frac{1-\sigma}{\sigma}\frac{R_r}{L_r} + \frac{1}{\sigma L_s}R_{sc}\right)i_{Lq} \\ -p\omega_r i_{Ld} - \frac{p\omega_r}{\varepsilon}\lambda_{rd} - \frac{R_r}{L_r}M\frac{i_{Lq}i_{Ld}}{\lambda_{rd}} \\ h_d(v_{sd}) = \frac{R_{cv}}{\sigma L_s}v_{sd} = \mu v_{sd} \\ h_q\left(v_{sq}\right) = \frac{R_{cv}}{\sigma L_s}v_{sq} = \mu v_{sq} \end{cases} \tag{2}$$

where R_c is the core loss resistance, $R_{sc} = \frac{R_s R_c}{R_s + R_c}$, $R_{cv} = \frac{R_c}{R_s + R_c}$ and $\varepsilon = \frac{\sigma L_s L_r}{M}$. The load current $i_L = \left[i_{Ld}\ i_{Lq}\right]^T$ is the difference between the stator current $\left(i_s\right)$ and the current $\left(i_f\right)$ consumed by R_c (Fig. 1) and given as

$$i_L = \left(\frac{R_s + R_c}{R_c}\right)i_s - \frac{v_s}{R_c} \tag{3}$$

The electromagnetic torque is described as follows:

$$C_e = p\left(\frac{3}{2}\frac{M}{L_r}\right)\lambda_r i_{rq} \tag{4}$$

Stator copper, rotor copper, and core losses dominate the overall IM power losses and can be defined as:

$$P_{tot} = P_c + P_f \tag{5}$$

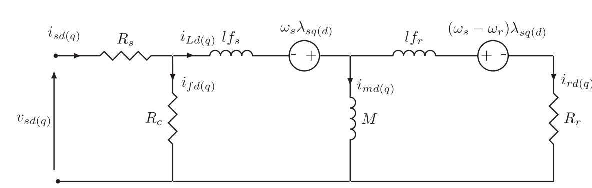

Fig. 1. Equivalent circuit of IM in (d, q) reference frame (lf_s, lf_r are stator and rotor leakage inductances receptively).