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Novel design model for the stator currents subsystem of induction motors

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ABSTRACT

The stator currents subsystem is a vital element of many high-performance induction motor control schemes. While there are several control techniques available for this subsystem, traditional linear controllers are still widely used because of its simplicity and proven effectiveness. However, the traditional simplified design-model lacks important information, necessary for the design of high-performance and robust controllers. In this article a novel design-model intended for linear controller formulation and evaluation is developed. This new mathematical representation captures several elements which are missing in the traditional representation, maintaining at the same time a similar level of simplicity. Along the derivation of this new representation several models of decreasing complexity and comprehensiveness are also presented together with a critical classification. This classification is intended to aid the designer in choosing the appropriate mathematical representation for specific purposes. Finally, the article is accompanied with experimental findings which illustrate the use of the proposed model.

1. Introduction

Induction motors are widely used as actuators in many industrial and research applications. Along the last decades the evolution of digital processing systems and power electronics made possible the extended use of high-performance induction motor control systems such as field oriented control (FOC) and direct torque control (DTC). Among these control strategies FOC has been traditionally shown to be a viable every-day solution for most induction motor control applications [1,2]. There are many kinds of FOC schemes. However, the most successful are based in rotor flux and torque decoupling [3]. Several recent schemes proposed in the literature are designed under this strategy [1,4–6]. These strategies aim for the induction motor to behave as a classical direct current (DC) motor. With DC motors it is easy to manipulate the flux and the torque separately by driving different physical currents, namely field and armature currents. However, induction motors do not share this characteristic. Therefore, non-linear control elements are introduced in order to produce virtual flux and torque producing currents. With the purpose of achieving this convenience, a two-step procedure is commonly used [1–3]. The first step consists of controlling the stator currents by using a voltage source inverter (VSI) as an actuator. By controlling the stator currents, the fifth degree non-linear model of the induction motor may be considered as a third degree

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system. The second step is to design a non-linear torque–flux control law. It is in this second step that most FOC schemes are introduced. Control strategies other than FOC may be used in the second step while preserving the stator currents control loop [7–11].

Some of the most successful control schemes for stator current control at an industrial level are based in classical linear PI or PID controllers and are still widely used [1,12]. These controllers are normally designed using a static or rotor-flux-aligned reference frame. In [12] it was shown that the performance difference between these approaches is negligible whereas the complexity of rotor-flux-aligned controllers is superior.

The induction motor stator currents subsystem is modeled by a fifth degree non-linear multiple-inputs multiple-outputs (MIMO) plant. Since this model may be cumbersome to use for classical PI-PID controller design, simplified design models are normally used. The classical simplified design model attempts to capture all the relevant system dynamics in a simple first order single-input single-output (SISO) linear system. This SISO system normally only depends on two out of five motor parameters and lacks information related to the rotor angular velocity [1,12–15]. In this article it will be shown how this model fails to represent some of the most important plant features, leaving the designer partially blind when setting the controller parameters. In particular, typical simplified design models lack vital information such as:

- The MIMO nature of the system. Even with the use of decoupling networks the designer must evaluate the robustness of the dynamics introduced under this scheme in the presence of perturbations and uncertainty.
- The rotor components. Some simplified models consider only stator elements based on steady-state electrical observations.
- The effects of rotor angular speed. It is important to recall that the stator currents subsystem is an inner control loop, and the full control scheme normally includes an outer speed control loop. The use of the outer speed control loop introduces particular operating conditions for the inner stator currents subsystem.

In this article a series of linear design models of varying complexities are presented. These models attempt to capture all the relevant multivariable interactions and non-linear aspects in increasingly compact representations. In order to propose better and simpler approximations, it is recognized that the stator currents control subsystem is normally an internal control loop of a more complex control system. By considering the resulting operating conditions of such a system, a novel single SISO linear transfer function is proposed. This transfer function presents several remarkable characteristics attractive for simplified control design and is covered in detail in Section 5.

Although the results here presented are generic and can be applied to any induction motor, a brief illustrative case study with real time experimental results is also included.

2. Non-linear induction motor model equation

The full induction motor model in a static reference frame is given by [14]:

$$\dot{i}_{\alpha s} = -\frac{L_r^2 R_s + L_m^2 R_r}{sigmaL_s L_r^2} i_{\alpha s} + \frac{L_m R_r}{\sigma L_s L_r^2} \psi_{\alpha r} + \frac{L_m \omega_r}{\sigma L_s L_r} \psi_{\beta r} + \frac{1}{\sigma L_s} v_{\alpha s},$$

$$\dot{i}_{\beta s} = -\frac{L_r^2 R_s + L_m^2 R_r}{\sigma L_s L_r^2} i_{\beta s} - \frac{L_m \omega_r}{\sigma L_s L_r} \psi_{\alpha r} + \frac{L_m R_r}{\sigma L_s L_r^2} \psi_{\beta r} + \frac{1}{\sigma L_s} v_{\beta s},$$

$$\begin{aligned}
\dot{\psi}_{\alpha r} &= -\frac{R_r}{L_r} \psi_{\alpha r} - \omega_r \psi_{\beta r} + \frac{L_m R_r}{L_r} i_{\alpha s}, \\
\dot{\psi}_{\beta r} &= -\frac{R_r}{L_r} \psi_{\beta r} + \omega_r \psi_{\alpha r} + \frac{L_m R_r}{L_r} i_{\beta s}, \\
T_E &= \frac{3}{2} \left(\frac{P}{2}\right) \frac{L_m}{L_r} (\psi_{\alpha r} i_{\beta s} - \psi_{\beta r} i_{\alpha s}), \\
\dot{\omega}_r &= \left(\frac{P}{2J}\right)(T_E - T_L),
\end{aligned} \tag{1}$$

where $i_{\alpha s}$ and $i_{\beta s}$ are the stator currents (control objectives), $\psi_{\alpha r}$ and $\psi_{\beta r}$ are the rotor fluxes, ω_r is the rotor angular velocity (electrical), $v_{\alpha s}$ and $v_{\beta s}$ are the stator voltages (control inputs), L_s, L_r, and L_m are the stator, rotor and mutual inductances, R_s and R_r are the stator and rotor resistances, J is the rotor inertia, T_L is the external torque load, T_E is the generated torque, P is the number of poles and $\sigma = 1 - L_m^2/(L_r L_s)$. This is the traditional model of the induction motor. Although additional considerations may be included, such as magnetic saturations, it is widely accepted that this model represents the actual induction motor adequately for most control purposes provided the parameters are properly identified.

In this article Eq. (1) is considered the ideal model and any additional transformations and/or simplifications are considered detrimental in the quality of the model. The preferred manipulations are the ones without loss of information. This aspect is assessed taking into consideration the loss of one-to-one relationships regarding stability and performance.