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In-depth cross-coupling analysis in high-performance induction motor control

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Abstract

High-performance field oriented control (FOC) of induction motors (IMs) relies on the accurate control of their electrical dynamics. In particular, perfect decoupling control of the stator currents should be ideally achieved for a FOC scheme to be efficient. However, the decoupling effectiveness afforded by most stator currents controllers may be influenced not only by the parameters and the operating condition, but also by the specific controller structure and the adopted coordinate system. A measure to assess decoupling effectiveness is non-existent in the IM control literature. To bridge this gap, an in-depth analysis of the cross-coupling inherent characteristics of the electrical subsystem of IMs under different well-known control structures is presented in this paper. Specifically, four control strategies previously studied and experimentally validated in the literature are critically assessed in this work: (1) stationary frame proportional-integral (PI) control, (2) synchronous frame PI control, (3) synchronous frame PI control with decoupling networks, and (4) improved stationary frame diagonal control. The decoupling capabilities of controllers in stationary and synchronous coordinates are examined, with a detailed insight on the role of decoupling methods. The analysis is performed in the frequency domain under the framework of individual channel analysis and design (ICAD). By application of ICAD, the decoupling effectiveness of FOC schemes is clearly exposed and quantified, with an assessment of the effects of parametric uncertainty being carried out for completeness. The effect of the inverter dynamics over cross-coupling is also treated using digital simulations. The results are useful to determine the conditions in which each control strategy has either advantages or disadvantages. Additionally, it is

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possible to determine the effect of several operating parameters over the stator currents cross-coupling such as nominal flux and torque levels.

1. Introduction

Induction motors (IMs) are the most commonly used high-power electric machines in several industrial applications. Originally IMs were employed in open-loop setups with limited energy efficiency. Further developments made possible a widespread adoption of closed-loop control, resulting in high-performance schemes with higher efficiency [1–3].

Field oriented control (FOC), also known as vector control, is a commonly adopted scheme for IM control [4–7]. Under ideal conditions, IMs employing rotor flux FOC schemes behave like dc motors. Conversely, stator flux FOC allows induction generators (IGs) to behave like dc generators. The approach enables stator or rotor voltages to be excited in such a way that the stator or rotor currents are decoupled. This produces flux- and torque-generating currents analogue to those of a dc machine [6,7]. In addition to a better transient performance, decoupling of currents allows IMs to be driven more efficiently.

The most popular FOC schemes for the stator currents are based on proportional-integral (PI) controllers [8–10], although significant effort has also been dedicated to non-linear decoupling schemes [11–18]. For low-performance applications a pair of stationary reference frame PIs is sufficient to comply with the required specifications, although a high-performance is also possible by introducing slightly more complex control structures [19]. The possibility of affording effective stator currents control that relies on simple PI structures as a baseline is due to the inherent structural robustness characteristics of the IM, as explained in detail in [20]. However, it is commonly accepted that a much higher performance may be attained through the use of controllers in a synchronous frame in addition to decoupling networks [9,21,22]. Such networks aim at decoupling the stator currents by introducing feed-forward terms that compensate the back electro-motive-force (emf) [8–10,23]. All of these control schemes have the ultimate objective of further reducing the cross-coupling of the stator current subsystem.

The electric subsystem of an IM is normally represented by a nonlinear fourth order multiple-input multiple-output (multivariable, MIMO) system [1–3]. It is common practice to simplify this model for control design, with simplifications going as far as using first order monovariable approximations with a time delay [1–5,8–10,19,24]. Although this approach has been successful, it could be argued that the control design is further influenced by the model [8,19]. Moreover, a fundamental limitation exists when neglecting or canceling the multivariable nature of the process, as it is not possible to assess the effect of detuned decoupling networks due to parametric variations. The interested reader is referred to [25], where a detailed analysis on the shortcomings resulting from model over-simplifications is reported. Similarly, it is not possible to compute the actual cross-coupling of the system to formally address the effectiveness of the decoupling scheme. Therefore, a theoretical study employing a unified measurement convention that allows comparing the resulting decoupling