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Research article

PI controller design for indirect vector controlled induction motor: A decoupling approach

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ABSTRACT

Decoupling of the stator currents is important for smoother torque response of indirect vector controlled induction motors. Typically, feedforward decoupling is used to take care of current coupling that requires exact knowledge of motor parameters, additional circuitry and signal processing. In this paper, a method is proposed to design the regulating proportional-integral gains that minimize coupling without any requirement of the additional decoupler. The variation of the coupling terms for change in load torque is considered as the performance measure. An iterative linear matrix inequality based H_∞ control design approach is used to obtain the controller gains. A comparison between the feedforward and the proposed decoupling schemes is presented through simulation and experimental results. The results show that the proposed scheme is simple yet effective even without additional block or burden on signal processing.

1. Introduction

Vector control in induction motor (IM) is used to make it behave like a separately excited direct current (DC) motor. The vector control of IM is realized in either of two ways: direct and indirect. Because of its simplicity and high performance, indirect one is often preferred over the direct one. To generate the instantaneous torque using indirect vector control (IVC) scheme [1], two current components (the direct and quadrature ones) are to be controlled independently. The available current-loop control schemes are based on synchronous reference frame control (SRFC), stationary reference control (SRC), and hysteresis control [2]. Although SRC is simpler than the SRFC one, the latter one is preferred since it operates on DC quantities and zero steady-state error. These benefits can be achieved if the regulator gains are chosen efficiently [2]. For such regulation, the reference quadrature current is given by the outer speed-loop, which is realized by linear, intelligent control techniques and nonlinear methods [3–8]. However, these components are inherently coupled through the motor dynamics which affects the IM torque response.

The coupled flux and torque dynamics behavior along with rotor resistance variation effect have been studied in [9]. The severity of this coupling on motoring operation depends on the control application. During the low-speed IM operation, the coupling effect can be neglected. Erstwhile, for high-speed operation, fast torque response is difficult to achieve without proper decoupling [10]. For overcoming the coupling effect, many decoupling techniques have been discussed. A complex vector synchronous frame proportional-integral (PI) controller design has been proposed in [11] to enhance the performance of synchronous PI controller. Specifically, parameter variation causes errors in the estimated flux that may lead to the reduction of the torque performance. To overcome this, a modified decoupling control has been proposed in [12]. Additional PI controller has been used to perform the decoupling in [13]. An internal-model-control (IMC) based decoupling has also been reported in [14], where additional integrator dynamics has been used to minimize the coupling. Further, a dynamic controller structure for the current controllers have been used in [10] to achieve decoupling. The rotor time-constant estimation based decoupling has been suggested in [15]. A new adaptive observer based speed estimation technique has been proposed in [16] that may be used for decoupling. Multivariable PI based decoupling scheme has been discussed in [17]. Here, similar to the IMC based decoupling [14], inclusion of integrators have been used for mitigating the coupling. Despite these modifications, the feedforward decoupling method [18] is still preferred due to its straight-forwardness and faster decoupling ability.

Apart from the above linear decoupling schemes, a sliding mode control based decoupling has been developed in [19,20]. Due to the lack of antiwindup capability in [19], the proposed controller may saturate at high speed limiting its application to

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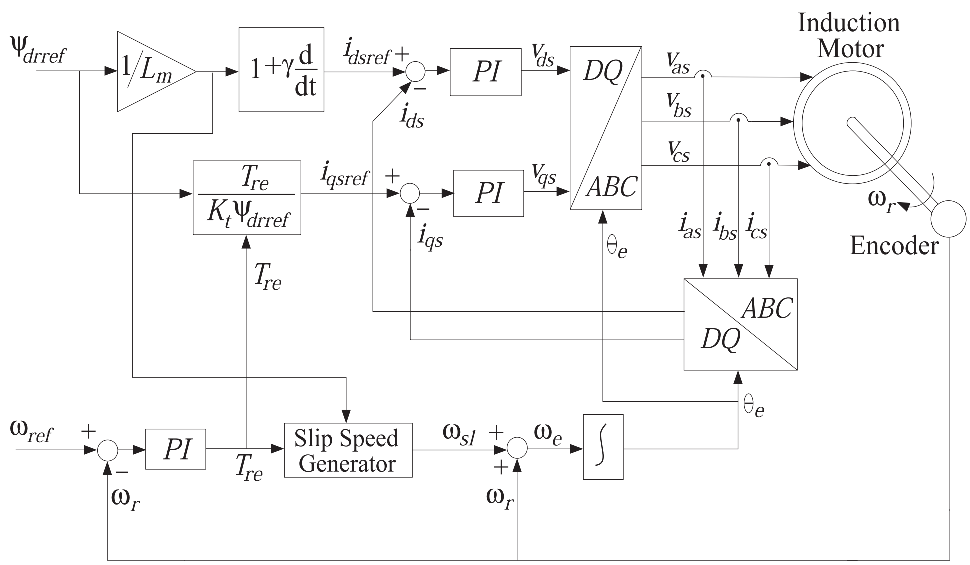

Fig. 1. Indirect vector control of induction motor.

low load conditions for which the coupling is itself weak. Also, it requires low-pass filters to remove the chattering effect. The decoupling is also been attempted in sensorless control scheme [21]. A nonlinear observer is proposed to estimate the motor speed, which is used to compensate the speed dependent cross-coupled terms. A modified IVC scheme based decoupling for current source IM drive has been given in [22]. Besides these decoupling methods, energy efficient model based control (MBC) has been discussed in [23] to improve the torque performance. In this work, the MBC dynamical behavior for load transition has been analyzed in detail and new control strategies have been proposed. In a recent work [24], an SRC based cascaded combination of a PI controller and a compensator has been designed for satisfying specified decoupling performance. In this scheme, no feedforward terms are employed, and the design criterion is simple based on gain margin (GM) and phase margin (PM) criterion. However, this robust stability based design involves a comparatively complicated structure than the conventional SRFC. In addition, since GM and PM of a multi-input multi-output (MIMO) system is involved in this design, the trade-offs of different performances, e.g., decoupling and robustness, are hard to obtain.

Modified PI controller based decoupling methods have been developed in [11,13,14,17]. However, all these methods incorporate additional dynamics and/or induce complexity in the conventional indirect vector controlled induction motor (IVCIM) system. Moreover, the tuning of the PI controller, otherwise used for current regulations, also has an impact on the coupling [19]. Despite the fact that such tuning has limited scope to minimize coupling. However, due to its simplicity and classical performance, it is considered as a better method for decoupling rather than introducing additional dynamics.

Typically, for designing a PI controller, frequency response (Bode plot) method is considered as simple. However, the robustness of the system is difficult to assess using such method [25]. On the other hand, for the controller design of finite dimensional linear time invariant systems, static output feedback (SOF) technique has been used in [26,27]. This technique has the advantages of simple closed-loop controller structure and flexibility of the design combined with an H_∞ control. The present work is on SOF based PI design of the speed as well as the current controllers to achieve decouple transient performance. By this method, the same classical IVCIM structure is retained. The following contributions are made in this work: (i) Sensitivity of stator currents on inner-loop controller gains is determined. (ii) The decoupling effect is formulated as a performance criterion for speed and current-loop controller design. (iii) An MIMO SOF based closed-loop structure is formulated for the linearized model of the IVCIM. (iv) An iterative linear matrix inequality (ILMI) based controller design technique is applied to design the PI gains. (v) Simulation and experimental results are presented that corroborates the effectiveness of the proposed controller design technique as compared to the conventional feedforward decoupling one.

The remaining of the paper is organized as follows: Section 2 presents the IVCIM model. The classical feedforward decoupler and sensitivity of stator currents are discussed in Section 3. Section 4 shows the formulation of the coupling minimization problem. The PI controller design algorithm is presented in Section 5. Comparison of the proposed method with feedforward one through simulation and experimental results is given in Section 6. Finally, conclusions are pointed out in Section 7.

2. State-space model of IVCIM

The IVCIM drive system [28,29] for speed regulation, is shown in Fig. 1. In this system, the rotor speed is regulated by an outer loop PI controller. The output of this controller is used to generate the torque and the flux reference components of the current. These reference currents are compared with the actual motor currents and applied to respective PI current controllers in order to regulate the input voltage to the induction motor. The IM model is structured with the underneath assumptions:

1. Both the stator and rotor windings are arranged symmetrically.
2. The following are neglected: the dynamics associated with nonlinear magnetic circuits; the harmonic content of the magneto motive force (MMF) wave; variation in rotor resistance due to the changes in temperature and frequency.
3. The load torque is considered as constant.
4. The reference flux is taken as the rated flux of the motor.

The dynamic induction motor model in synchronous reference frame is given by [28]: