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Power control of a doubly fed induction machine via output feedback

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Abstract

A new output feedback control algorithm for a doubly fed induction machine (DFIM) is presented. The asymptotic regulation of active and reactive power is achieved by means of direct closed-loop control of active and reactive components of the stator current vector, presented in a line-voltage-oriented reference frame. To get the maximum generality of the solution, the usual assumption of negligible stator resistance is not made. A full-order DFIM model is used for the control algorithm development. The proposed control system is robust with respect to bounded machine parameter variations and errors on rotor position measurement. In the paper, it is also shown how the proposed current control algorithm can be modified in order to achieve asymptotic active current tracking and zero reactive current stabilization during steady state. An extension for the speed control objective and output EMF control during the excitation–synchronization stage are also presented. Simulation and experimental tests demonstrate high dynamic performance and robustness of the control algorithm for typical operating conditions. The proposed controller is suitable for both energy generation and electrical drive application with restricted speed variation range.

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1. Introduction

A vector-controlled doubly fed induction machine (DFIM) is an attractive solution for high-performance restricted speed-range electric drives and energy generation applications (Leonhard, 1995). In Fig. 1, the typical connection scheme of this machine is reported. The stator windings are directly connected to the line grid, while the rotor windings are supplied by a bi-directional power converter. This solution is suitable for all of the applications where limited speed variations around the synchronous speed are present. Since the power handled by the rotor side (slip power) is proportional to the slip,

the energy conversion requires a rotor-side power converter which handles only a small fraction of the overall system power. Moreover, when the DFIM is used as a variable-speed drive, the slip power is regenerated during motor operating conditions by the rotor-side converter to the line grid, resulting in highly efficient energy conversion. Electric energy generation systems operating at variable speed have several advantages when compared with fixed-speed synchronous and induction generation. In generation systems driven by a diesel engine, the variable-speed operation depending on the generated power allows for a reduction of fuel consumption. In hydroelectric generation systems it increases the energy efficiency up to 10%. In wind energy generation systems the adjustment of the shaft speed as a function of the wind speed permits a higher energy capture by maximizing the turbine efficiency. Reduction of the torque ripple in the drive train due to torsional mode resonance can be

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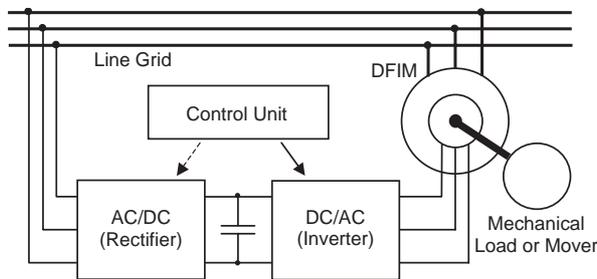


Fig. 1. Typical connection scheme of a DFIM.

additionally achieved with variable-speed operation (Nakra & Duke, 1988).

An important feature of the vector-controlled DFIM reported in Leonhard (1995) and Vas (1990) is the possibility to achieve decoupled control of the stator-side active and reactive power in both motor and generator applications. Moreover, if a suitably controlled AC/AC converter is used to supply the rotor side, the power components of the overall system can be controlled with low-current harmonic distortion in the stator and rotor sides.

The fundamentals of DFIM vector control are presented in Leonhard (1995). Different strategies were proposed to solve the DFIM control problem. The most important results are reported in Leonhard (1995), Pena, Clare, and Asher (1996a) and Hopfensperger, Atkinson, and Lakin (2000). All of them are based on the classical concept of field orientation (stator or air-gap flux) used as a torque–flux decoupling technique for induction motor control. Since in DFIM both stator and rotor currents are available from measurement, the flux vectors (stator, air-gap or rotor) can be computed using flux–current correlation equations. Consequently, the DFIM control problem is typically classified as a nonlinear state-feedback problem.

Under the assumption of rotor current-fed DFIM and negligible stator resistance, the torque and stator-side reactive power control problem is transferred to rotor current control if the rotor currents are defined in a field-oriented reference frame. Torque (active power) or speed control objective, together with the stator-side reactive power regulation (stabilization) are typically considered.

The structure of a standard DFIM controller includes two-axis high-gain rotor current control loops with PI current controllers, implemented in a flux-oriented reference frame. Two rotor current references are used as scaled references for torque and reactive power. The solutions based on direct stator flux orientation, reported in Leonhard (1995), Yamamoto and Motoyoshi (1992), Pena et al. (1996a), Hopfensperger et al. (2000), Walczynna (1991), rely on some simplifying assumptions. In particular, stator resistance is usually

considered negligible. This hypothesis, which is typical for high-power DFIMs, leads to neglect also the stator flux poorly damped dynamics in the controller design since the stator flux vector is always assumed constant in quadrature with the line-voltage vector. As far as the authors know, no analytically proven full-order control algorithms based on the stator flux field orientation are available in literature. State-feedback linearization has been applied in Bogalecka and Kzreminski (1993) to solve the DFIM control problem. The assumption of current-fed rotor is used with an additional first-order filter in the control loop. Rotor position sensorless solutions have been considered in Xu and Cheng (1995), Hopfensperger et al. (2000) and Bogalecka (1993). The operation of a vector-controlled DFIM supplying an isolated load is reported in Pena, Clare, and Asher (1996b). The classical approach for DFIM vector control (Leonhard, 1995) requires measurements of stator, rotor currents and rotor position. In order to achieve synchronization with the line-voltage vector for soft connection to the line grid, the information about line voltages is also needed. Exact knowledge of induction machine inductances (including the saturation effect) is required to compute fluxes from currents. The necessity for high-precision rotor position measurement has been addressed in Xu and Cheng (1995). In Pena et al. (1996a, b), the authors use the integration of stator voltage equations in order to estimate stator fluxes. This solution requires particular adjustments to avoid open-loop-integration drift due to variations of stator resistance and measurements offset. However, it must be underlined that the compensation of such effect for DFIMs is less difficult than for typical induction motor drives. In fact, the stator flux components in a fixed a–b reference frame are sinusoidal with a frequency equal to that of the line grid and the stator resistances are very small in large DFIMs, usually adopted in industrial practice. Different approaches for the implementation of the stator flux-oriented reference frame are discussed in Hopfensperger et al. (2000).

In Peresada, Tilli, and Tonielli (1998), an alternative approach for the design of DFIM active–reactive power control is proposed. The controller development is based on implementation of a line-voltage vector-oriented reference frame. Since the line-voltage vector can easily be measured with negligible errors, this reference frame is DFIM parameter-independent in contrast to the field-oriented one. Moreover, information about line voltage is typically needed in order to perform the soft connection of the DFIM to the line grid during the preliminary excitation–synchronization stage. This full-order control algorithm ensures globally asymptotically stable torque tracking and stator-side unity-power-factor. It is demonstrated that conditions of stator flux field orientation and line-voltage vector orientation are equivalent if the stator-side power factor

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