Available online at www.sciencedirect.com
ScienceDirect
IFAC PapersOnLine 50-1 (2017) 13129–13135

Integrated Control of Motion and Contactless Power Transfer for Doubly-Fed Induction Machines in Complex Rotary Apparatuses

Andrea Tilli * **Alessandro Bosso** * **Christian Conficoni** * **Ahmad Hashemi** *,**

* *Department of Electrical, Electronic and Information Engineering, University of Bologna, Bologna, Italy (e-mail: {andrea.tilli,alessandro.bosso3,christian.conficoni3,ahmad.hashemi}@unibo.it).*
** *Electrical Eng. Dept., Sama Technical and Vocational training College, Islamic Azad University, Kermanshah, Iran*

Abstract: A novel control solution for Doubly-Fed Induction Machines is proposed to enable new applications of such kind of machines. This strategy guarantees a fully decoupled motion control and contactless power transfer between stator and rotor, by using controlled inverters on both stator and rotor side. For large and complex rotary apparatus with relevant electric loads and actuators placed on-board the mobile part, the proposed solution allows to exploit direct-drive versions of Doubly-Fed Induction Machines for both moving and feeding independently the rotating part, where the rotor-side converter has to be hosted. Power transfer is attained through two different working principles in order to achieve decoupling from the torque references and to suitably deal with voltage saturations on power converters. Global asymptotic stability proof is provided for this control strategy. Simulation results are reported in order to validate the promising theoretical developments.

Keywords: Power systems; Energy systems; Systems with saturation.

1. INTRODUCTION

Doubly-Fed Induction Machines (DFIMs) are widely used in *Variable Speed Constant Frequency* (VSCF) systems, i.e. renewable energy systems (wind turbines, small-scale hydroelectric generators), embedded applications (electric aircrafts and vehicles), and Flywheel Energy Storage Systems (FESS). High energy efficiency is the most inspiring aspect about DFIMs, owing to the fact that they are fully controllable through the rotor side winding, fed by Voltage Source Inverters (VSIs) and with the stator winding directly connected to the power grid. This enables the use of lower power electronic inverters (typically around 30% of the rated power) only at rotor side. In this architecture, the most common method to supply the rotor circuit is to use brushes and slip rings, widely covered in literature (Liang et al., 2010), (Breban et al., 2007), (Wang et al., 2011). Besides, some solutions have been proposed to fed the rotor, without such devices, relying on suitable transformers (Zhong et al., 2015).

The subject of this paper is to introduce a novel control problem for DFIMs, whose corresponding proposed solution enables a new particular exploitation of this kind of machine to address multiple relevant requirements of complex rotary machineries. Many industrial and civil applications include large mechanical rotating apparatuses whose motion has to be accurately controlled and which host multiple actuators on the moving part, that require relevant amounts of electric power to be transferred to that side. Rotary tables for automatic machines, vertical axis mills, and carousels provide some relevant examples in this direction (Zrin and Fink, 2009). For such rotary machines, beside standard drives and reducers to generate and control the motion, the typical solution to transfer power to the rotor side is to use brushes and slip rings (da Costa et al., 2011). Despite being a mature technology, carbon brush slip-ring systems, producing conductive dust during operation, are highly sensitive to environmental conditions. Other solutions based on gold-alloy contacts are very expensive and have an expected lifetime strongly dependent on the working conditions (Holzapfel, 2012),(Chen et al., 2016). To avoid these drawbacks, some studies have proposed *Rotary Transformers* (RTs), particular devices mounted on the shaft in order to supply the rotating components independently (Zhong et al., 2015), (Ditze et al., 2016). Nevertheless, RTs impose an extra bulky electromechanical hardware to the system.

Taking the cue from the above considerations on complex rotary machineries and recalling the main features of DFIMs, in this paper, we propose a new control algorithm for DFIM aiming at controlling independently its electromagnetic torque and the power transferred to rotor side. For this purpose, we consider a DFIM endowed with two controlled power converters to feed rotor and stator windings, named *Rotor Side Converter* (RSC) and *Stator Side Converter* (SSC), respectively. Therefore, we refer such system as Doubly-Inverter-Fed Induction Machine (DIFIM). The proposed control solution will enable to effectively use *direct-drive* DIFIM to move complex rotary apparatus and feed the electric and electromechanical loads and actuators hosted on the moving part. To this purpose, the architecture depicted in Fig. 1 has to be adopted; in particular the

10.1016/j.ifacol.2017.08.2166

RSC has to be placed on-board of the rotating part and its DC-link will be used as DC-supply to feed the on-board devices [1]. A similar architecture has been presented in (Schneider et al., 2015), but there the focus has been on linear machines with a different control approach.
The control algorithm presented in this paper is a modification of common field-oriented control to effectively decouple torque and rotor power control. To this purpose, two possible mechanisms to transfer power from stator to rotor side (and vice-versa) are suitably combined, also to prevent voltage saturation in the power converters. The two power transfer mechanisms are:

- exploiting the mismatch (i.e. the slip) between the rotating speed of constant-amplitude field generated form stator side and the mechanical speed of the rotor;
- using a stator field rotating synchronously w.r.t. rotor, but with pulsating amplitude.

The former is quite natural and linked to normal usage of DFIM, but it is applicable as long as a non-null and actually large enough torque is imposed between stator and rotor, otherwise too large synchronous speed and voltages would be necessary. Conversely, the latter is theoretically feasible in any condition, but it requires magnetic fields rotating with pulsing amplitude, then it is quite unconventional and prone to magnetic saturation. Moreover, this technique leads to oscillations in the transferred power in such a way that only the mean value of the power can be effectively controlled.
In more detail, the proposed control strategy is organized as follows. Current and flux references are designed in order to:

- decouple torque and power transfer objectives, even in case of time-varying torque references;
- distribute the power target as follows: the constant amplitude field is exploited as long as the synchronous speed is still acceptable to prevent voltage saturation (i.e. until the torque is still large enough w.r.t. the current speed), otherwise the exceeding power is moved smoothly to the pulsating field mechanism.

Given the above-mentioned references, feedforward terms based on them are defined for both stator and rotor voltages. Then feedback terms based on stator side current errors are added to stator side voltages.

The reminder of the paper is organized as follows. In Section 2, the DIFIM model and detailed control objectives are introduced. Sections 3 and 4, respectively, present the references generation and control laws used to accomplish the task. Section 5 shows the simulation results. In simulation test the machine parameters are derived, figuring out a direct-drive DIFIM with a nominal power of $5kW$ and a nominal speed of $60rpm$. Finally, Section 6 concludes the paper, summarizing the main results and pointing out important technological issues and potential developments of the presented control solution.

[1] It is worth noting that direct-drive feature (i.e. with no mechanical reducer) is crucial to have rotor windings of DIFIM linked to the rotating part and, then, to bring power directly there without slip rings or RTs. On the other hand, direct-drive DFIM are not common. Special machine design is necessary to deal with low speed, high torque and mechanical constraints related to the rotating apparatus. This point is not considered here, since the purpose of the paper is to show how the proposed control technique can open the path to such solution.

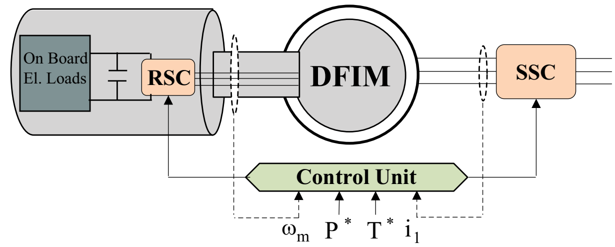

Fig. 1. Typical connection scheme of the integrated motion control and power transfer system with direct-drive DIFIM.

2. MODEL AND PROBLEM STATEMENT

Under standard hypotheses of balanced operating conditions, linear magnetic circuits, negligible iron losses and end-windings effects, the electromagnetic dynamic model of the DFIM or DIFIM, as well, in a generic two phase rotating reference frame $(u-v)$ [2] reads as follows (Leonhard, 2001):

$$
\begin{aligned}
\dot{i}_{1u} &= -\gamma_1 i_{1u} + \omega_0 i_{1v} + \alpha_2\beta_1\varphi_{2u} + \beta_1\omega_r\varphi_{2v} - \beta_1 u_{2u} + u_{1u}/\sigma_1 \\
\dot{i}_{1v} &= -\gamma_1 i_{1v} - \omega_0 i_{1u} + \alpha_2\beta_1\varphi_{2v} - \beta_1\omega_r\varphi_{2u} - \beta_1 u_{2v} + u_{1v}/\sigma_1 \\
\dot{\varphi}_{2u} &= -\alpha_2\varphi_{2u} + (\omega_0-\omega_r)\varphi_{2v} + \alpha_2 L_m i_{1u} + u_{2u} \\
\dot{\varphi}_{2v} &= -\alpha_2\varphi_{2v} - (\omega_0-\omega_r)\varphi_{2u} + \alpha_2 L_m i_{1v} + u_{2v} \\
T_m &= \eta_1(\varphi_{2u} i_{1v} - \varphi_{2v} i_{1u}),
\end{aligned}
\tag{1}
$$

where i_{1u}, i_{1v} are the stator currents, φ_{2u}, φ_{2v} are the rotor fluxes, $(u_{1u}\ u_{1v})$ and $(u_{2u}\ u_{2v})$ are stator and rotor voltages, respectively, ω_r and ω_0 are the electrical angular speeds of the rotor and the rotating reference frame, while T_m is the resulting electromagnetic torque. Throughout this paper, according to standard nomenclature, *stator* and *rotor* will be also referred as *primary* and *secondary*, respectively. The parameters used for the model are a compact representation of these expressions:

$$
\begin{aligned}
\sigma_1 &= L_1\left(1-\frac{L_m^2}{L_1L_2}\right), \beta_1 = \frac{L_m}{\sigma_1 L_2}, \alpha_2 = \frac{R_2}{L_2}, \\
\gamma_1 &= \left(\frac{R_1}{\sigma_1} + \alpha_2\beta_1 L_m\right),\ \eta_1 = \frac{3pL_m}{2L_2}.
\end{aligned}
\tag{2}
$$

In (2), R_1 and R_2 are stator and rotor resistances, p is the number of motor pole pairs, whereas L_1, L_2 and L_m are stator and rotor auto-inductances and mutual inductance, respectively. Using this representation for DFIMs, it is easy to retrieve the expressions for primary and secondary power P_1, P_2, as well as the mechanical output power P_m:

$$
\begin{aligned}
P_1 &= \frac{3}{2}(u_{1u}i_{1u} + u_{1v}i_{1v}) \\
P_2 &= \frac{3}{2}(u_{2u}i_{2u} + u_{2v}i_{2v}) \\
P_m &= \frac{1}{p}T_m\omega_r,
\end{aligned}
\tag{3}
$$

where i_{2u} and i_{2v} are the rotor currents, which are related to stator currents and rotor fluxes as follows:

$$
i_{2u} = \frac{\varphi_{2u} - L_m i_{1u}}{L_2}, \quad i_{2v} = \frac{\varphi_{2v} - L_m i_{1v}}{L_2}. \tag{4}
$$

2.1 Problem Statement

Model (1)-(3), together with the proposed architecture of Fig. 1, is composed of 5 control inputs, which are primary and secondary voltages and the reference frame speed ω_0, whereas several possible output signals can be outlined, depending

[2] standard Blondel-Clarke-Park amplitude-preserving transformations have been applied to turn three-phase variables into two-phases vectors represented in a specific reference frame