Generic study of the power capability of a cascaded doubly fed induction machine

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Abstract

The paper deals with the steady state power operating margins of a cascaded doubly fed induction machine. A generic analytic method, based on a per unit representation, is suggested to derive systematically the active-reactive power domain. Therefore, the study can be applied to different ranges of doubly fed induction machines. The limit curves are defined in terms of the rated quantities of the machine. The effect of magnetic circuit saturation is further investigated. It is shown that the power capability is determined by the stator current maximum values and is subject to several limitations. The analytical approach is tested and validated by experimental measurements.

1. Introduction

Due to the recent interest in renewable energy and embedded power generation systems, the development and control of Variable Speed Constant Frequency (VSCF) generators have become a very important research topic. Among the possible types of VSCF generators is the Doubly Fed Induction Machine (DFIM). This generator is widely used in autonomous and grid-connected wind energy applications [1–3]. It is able to provide reactive current and supply constant frequency voltages at variable speed using partially rated converters [4,5]. Nevertheless, the presence of brushes and slip rings in this classical structure increases significantly the maintenance cost and reduces the system reliability [6,7]. An alternative solution for conventional DFIM replacement is a Cascaded Doubly Fed Induction Machine (CDFIM). This configuration retains the benefits of the single wound rotor induction machine in a brushless structure that provides robustness, reliability and low maintenance cost which are fundamental in the above-mentioned applications [8,9].

The CDFIM consists of two wound rotor induction machines coupled mechanically and electrically through their rotors. The stator of the Power machine M2 is directly connected to the main supply, while the stator of the Control machine M1 is fed by a reduced power bidirectional back-to-back converter (Fig. 1). The CDFIM is the basic concept of a doubly fed brushless machine. This early version has then evolved from a structure based on two separated machines to a single compact electric machine with a dual-tapped stator windings wound into a common stator core [10]. The rotor is specially designed to induce a cross-coupling effect between the two stator windings. Its configuration can be divided into special nested cage type and reluctance type, introducing two descendants of the CDFIM: the Brushless Doubly Fed Induction Machine (BDFIM) and the Brushless Doubly Fed Reluctance Machine (BDFRM) respectively [11].

Previous works have investigated the operation of the CDFIM as a VSCF generator in various grid-connected and standalone applications including windmills [12,9], small scale hydro-power systems [13], and embedded aircraft industry [8]. The research effort has focused on the stability, the dynamic performance and the development of new control schemes under grid disturbances and normal grid conditions [9,12,14–16]. However, the power sizing of the CDFIM was rarely treated in the literature, although it is of great importance for practical applications. In fact, it ensures the machine is being operated in a state within its ratings and allows to choose the appropriate machine that is best adapted for the intended application, according to its power capability limits. It also reveals the contribution of the machine to reactive power generation, as required by the corresponding grid codes and/or the load demands [5,17]. This is essential for the design of a generating unit in order to plan the reactive power resources. Particularly in
wind energy systems, where grid utilities require extended reactive power supply in support of grid voltage not only during voltage dips but also in normal operation [18,19]. For this purpose, the power operating margins of the CDFIM and its ability to provide reactive power are to be investigated.

A theoretical power operating chart of a brushless doubly fed induction machine showing the limits imposed by resistive heating of the windings, magnetic loading and load angle is presented in [20]. Nevertheless, the analytical expressions of the limit curves are not derived. The limit boundaries were found iteratively by simulations for a particular machine by sweeping the control voltage over its whole phase and magnitude range. A preliminary analytic approach was elaborated in a previous paper [21] to derive the steady state power region of the CDFIM regarding its rated quantities. Yet, the magnetic circuit saturation was not taken into consideration in the study. In addition, the proposed method was validated by simulations only and it was limited to the particular case of a CDFIM based on two identical 2.2 kW induction machines. This paper presents a more generic study. The performance of a CDFIM in terms of power flow, converter sizes and system efficiency depends on the rotor interconnection type and the numbers of pole pairs \( p_1 \) and \( p_2 \) of both DFIMs. 1 and 2 subscript refer to DFIM1 and DFIM2 respectively. Theoretical, the two wound rotor induction machines can have any pole pair combination with rotors connected in inverse or direct coupling sequence. Nevertheless, a rigorous analysis established in [8] has shown that direct coupling must be avoided; the only satisfying performances for generating systems are achieved by an inverse interconnection configuration with \( p_1 \geq p_2 \). In the following, the per unit system is first defined, then the machine equations are elaborated.

2. Modeling of the cascaded doubly fed induction machine

The performance of a CDFIM in terms of power flow, converter sizes and system efficiency depends on the rotor interconnection type and the numbers of pole pairs \( p_1 \) and \( p_2 \) of both DFIMs. A theoretical, the two wound rotor induction machines can have any pole pair combination with rotors connected in inverse or direct coupling sequence. Nevertheless, a rigorous analysis established in [8] has shown that direct coupling must be avoided; the only satisfying performances for generating systems are achieved by an inverse interconnection configuration with \( p_1 \geq p_2 \). In the following, the per unit system is first defined, then the machine equations are elaborated.

2.1. Per unit system

In this study, per unit system is employed in order to formulate generalized conclusions. Base values of the per unit system for each induction machine, are defined in Table 1.

The base value of the transformer (stator to rotor) turns ratio given by:

\[ m = \frac{L_{2p}}{L_{1p}} \approx \frac{L_{2d}}{L_{1d}} \text{ and } X_0 \text{ the RMS rated value of quantity } \lambda X_0 \text{.} \]

The base voltage is chosen as the phase-to-neutral voltage. Therefore, the DFIM electrical parameters, referred to the stator side, can be expressed in per unit form as follows:

\[ r_i = \frac{R_i}{m^2 Z_{isbi}}; \quad x_i = \frac{L_{isbi}}{Z_{isbi}}; \quad x_{hi} = \frac{M_{isbi}Z_{isbi}}{m_i^2 Z_{isbi}} \]

\[ x_{hi} = \frac{L_{isbi}}{m_i^2 Z_{isbi}} \quad i = 1, 2 \]
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