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Power operating domain of a cascaded doubly fed induction machine

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Abstract

The paper deals with the steady state operating limits of a cascaded doubly fed induction machine (CDFIM) in terms of active and reactive powers. An analytic method is suggested to derive the power region, in which the machine can operate safely without exceeding its rated parameters. The proposed steady-state analytical study has been thoroughly validated by simulations using an elaborated model of the CDFIM implemented on Matlab-Simulink. It is shown that the power capability is subject to several limitations. For a limited speed range the reactive power consumption and generation are determined by the stators current maximum values. The study is further extended to illustrate the effect of the slip range and the terminal voltage on the power limit curves.

Keywords: Cascaded doubly fed induction machine; Steady state operating margin; Power diagram; Wind turbine

1. Introduction

The Doubly Fed Induction Generators (DFIGs) are potential candidates for high power wind energy conversion systems because they are able to generate reactive current and produce constant-frequency electric power at variable speed operation. Independent regulation of active and reactive powers is accomplished by means of converters sized for a fraction of the nominal power (20%–35%) depending on the speed range and the reactive power requirements [6].

However, the main drawback of the DFIG is its brushes and slip rings structure, which involves permanent maintenance and reduces the life time of the machine [14]. Since wind energy applications are usually located in remote places, a high mean time between failures is required. Among alternative solutions is the Cascaded Doubly Fed Induction Generator (CDFIG). If the rotor windings of a given DFIG should be supplied by another three phase ac machine, a second DFIG is introduced leading to a complete brushless structure [4,10]. The CDFIG presents a similar behavior to a single DFIG and can be directly connected to the grid. The concept of a CDFIG based wind turbine is illustrated in Fig. 1; it is based on two wound rotor induction machines connected in cascade, with their rotor mechanically

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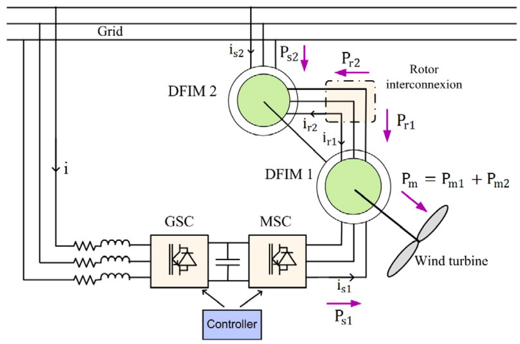

Fig. 1. Configuration of a grid connected CDFIG.

and electrically coupled. The stator of the Power machine (M2) is directly connected to the grid, whereas the stator windings of the Control machine (M1) are connected to the grid via a bidirectional fractionally rated converter.

Due to the considerable progress of wind power generation systems, the grid codes requirements for large wind farms are becoming more restrictive and similar to conventional power plants. Extended reactive power supply is required not only under network faults but also in normal grid conditions. Indeed, during steady state performance, generating plants should be able to operate at different power factors (leading or lagging) depending on the voltage level at the point of common coupling. Besides, following voltage dips, wind turbines should remain connected to the grid and must supply reactive power and participate to the voltage regulation [3,15]. Much research effort has focused on the stability and development of new control schemes for the CDFIG [5,8,12,13], yet no consideration has been given to define the safe operating domain of the generator, with regards to its ratings, and its contribution to reactive power generation required by grid codes.

For this purpose, a rigorous analytic study is elaborated in this paper, that derives systematically the steady state operating margin of a CDFIM considering its rated parameters. Based on the conventional model of the generator in the unified synchronous rotating frame, the active versus reactive power diagram is established. This is followed by multiple results revealing the influence of the slip range and terminal voltage variation on the reactive power capability of the machine. Simulation tests are performed on a grid connected CDFIG in order to validate the analysis presented in this manuscript.

2. Steady state analysis of a CDFIM: frequency and power flow behavior

Presently, the major interest of a CDFIM is the operation in synchronous mode. The machine is able to operate stably as a brushless variable-speed generator over a wide speed range with controllable dynamic response [1]. The synchronous operation occurs when the rotors current induced by both Power and Control machines evolve with the same frequency. Therefore, according to the mechanical speed variation, the Control machine stator frequency is adjusted in order to maintain the synchronous mode. Besides, by controlling the voltage phase and magnitude, the active and reactive power flows in the machine can be dynamically adjusted.

Starting with a single DFIM, the steady state operation is characterized by relations (1)–(5). The expressions refer to the supersynchronous motor convention (Fig. 1) and are based on a simplified model of the machine where copper/iron losses and magnetic leakages are neglected.

$$P_r = -g P_s \tag{1}$$

$$Q_r = -g Q_s \tag{2}$$

$$P_m = P_r + P_s = (1 - g) P_s \tag{3}$$

$$w_s = w_r + p\Omega \tag{4}$$

$$g = (\omega_s - p\Omega) / \omega_s = \omega_r / \omega_s \tag{5}$$

where:

ω_s: stator frequency in rd/s,

ω_r: rotor frequency in rd/s,