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Control methodology for compensation of grid voltage unbalance using a series-converter scheme for the DFIG

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ABSTRACT

This paper proposes a control methodology for compensation of grid voltage unbalances using a new scheme of doubly fed induction generator (DFIG) based on a series grid side converter (SGSC), the series-DFIG scheme. In such DFIG scheme, the grid side converter (GSC), which is usually connected in parallel to the machine stator, is replaced by the SGSC, connected in series with the machine stator. The proposed control methodology exploits the potential of the series-DFIG scheme to avoid that grid voltage unbalances compromise the machine operation, and to compensate voltage unbalances at the point of common coupling (PCC), preventing adverse effects on loads connected next to the PCC. This methodology uses the rotor side converter (RSC) to control the negative sequence current injected through the machine stator and the SGSC to control the negative sequence stator voltage to minimize the electromagnetic torque oscillations. The proposed control methodology is validated by simulation results.

1. Introduction

Wind power has become one important source of energy. Due to the characteristics of regions with good wind energy availability, wind turbines are frequently connected to power grids susceptible to unbalanced grid voltage conditions due to their placement in remote or rural areas. Unbalanced grid voltages are caused by different factors as: asymmetrical loads, transformer windings, asymmetrical transmission impedances and grid faults [1,2]. They are responsible for operation issues, such as electrical machine overheating, transformer overloading, and capacity limitation of power electronic devices. Such issues have encouraged the publication of standards and guidelines to limit the operation when voltage unbalances are present, as the one from the National Electrical Manufacturers Association (NEMA) in Standards Publication no. MG 1-1993 [3], which recommends the derating of asynchronous machines under voltage unbalances up to 5%, and does not recommend the operation above this limit.

In the past, as the penetration of wind power was very low, the wind turbine connection requirements were focused mainly on the turbine protection and, in case of disturbances, the wind turbines were simply disconnected from the grid. This scenario has changed and, currently, wind turbines should remain connected during system disturbances and, in some cases, wind turbines are required to actively support the grid. Among the possible disturbances, voltage unbalance is responsible for a poor wind generator performance and it is an important cause of partial or total disconnection of wind parks [4,5]. As a consequence, some strategies for the operation of wind turbines under unbalanced voltage conditions have already been proposed and are still evolving towards an effective solution.

Among the current technologies used for wind energy conversion, the Doubly Fed Induction Generator (DFIG) has been one of the most employed in the last years due to its operational flexibility. When this generator is subjected to even a small unbalanced grid voltage, it presents highly unbalanced stator and rotor currents [5]. These unbalanced currents are responsible for oscillations in the electromagnetic torque, compromising the machine integrity [6]. When the grid operation is analyzed, the unbalanced machine operation can increase the grid voltage unbalance level, once the machine presents low negative sequence impedance.

Several control strategies have already been proposed for DFIG operating under unbalanced voltage conditions. The most of them have focused on compensating the negative effects of grid unbalanced voltages on the generator operation [7–13]. Other strategies focus on improving the grid voltage unbalance levels by injecting a negative sequence current [1]. The objectives of the negative sequence current injection usually are: to reduce the unbalanced current flowing in the grid; to reduce the voltage unbalance at the

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Point of Common Coupling (PCC); or to improve the whole grid voltage unbalance profile.

The natural solution for voltage unbalance compensation is to use the converters already present in DFIG for this task. In a conventional DFIG, the machine rotor is coupled to the grid by a bidirectional converter, which is composed by the Rotor Side Converter (RSC), the DC link and the Grid Side Converter (GSC). The RSC is connected to the rotor windings and the GSC is connected in parallel with the machine stator winding and the PCC.

As the rotor machine currents can be controlled by the RSC, such control can be used (a) to reduce the electromagnetic torque oscillations produced by the stator unbalanced voltages [8–17]; or (b) to inject a negative sequence current in the grid through the machine stator [1]. It is also possible to inject a negative sequence current by the GSC [1,18,19] which can be used either to compensate the machine own influence or to minimize the grid voltage unbalance, as long as there is a residual power available in the converter. A coordinated solution combining the RSC and GSC negative sequence controls [1,20,21] tends to be more efficient. However, the techniques using the conventional DFIG are limited by the remaining capacity of the converters, which depends on the point of operation of the generator.

Another solution to reduce the DFIG susceptibility to voltage disturbances has been developed [22], by inserting a third converter based on Dynamic Voltage Restorer (DVR) architecture. This solution allows the compensation of the machine stator voltage from any disturbance of the grid voltage. The third-converter, called Series Grid Side Converter (SGSC), is coupled by a series transformer to the machine terminals and shares the DC link with the GSC. In [23] an improved voltage ride through capability of this DFIG topology has been observed when compared to the traditional scheme. This configuration has also a better capability to deal with network unbalanced conditions [24].

In order to avoid the extra cost of a third converter, a two-converter series topology in which the SGSC replaces entirely the GSC functions, has been proposed [25–27]. To achieve this objective the DC-Link voltage control was integrated to the SGSC. This DFIG topology has allowed to combining the capacity to deal with voltage disturbances of the three-converter series topology with the lower cost of the two converters of a traditional DIFG scheme. It is worth to highlight that, compared to the conventional DFIG scheme, the series-DFIG presents a considerable higher potential to compensate the voltage unbalance at the PCC due its capacity to control the stator voltage.

Although the series compensation of the series-DFIG scheme can improve the voltage unbalance levels at the PCC, so far no control strategies have been proposed for this task using this scheme. This task requires a coordinated control of the converters to inject the negative sequence current and the compensation of the torque oscillations due to these currents in the machine. To accomplish this, the present study proposes the control of the negative sequence current by the RSC, and the control of the stator voltage by the SGSC to minimize the torque oscillations.

In this context, a control strategy to compensate grid unbalanced voltages using the series-DFIG scheme is developed in this paper. The contributions of the proposed control methodology are: (a) exploiting a new DFIG configuration, which presents the functions of a DVR without the need of an additional converter; (b) protecting the integrity of the machine under grid voltage unbalances conditions; (c) minimizing or even eliminating the grid voltage unbalance at the PCC, therefore preventing issues associated with loads connected to grid sensitive to voltage unbalances.

The paper is organized as follows: Section 2 provides the proposed configuration of the DFIG operation under unbalanced currents and the machine dynamic model which is used in Section 3 to show the proposed control methodology. The methodology is validated by simulation results presented in Section 4. Finally, in Section 5 the main conclusions are presented.

2. System architecture and model

The insertion of the SGSC as a third converter in the traditional DFIG topology has proved to improve the capacity of the DFIG to respond to voltage sags, swells and faults in the grid, since it enables controlling the stator terminal voltage by regulating the output voltage of SGSC [23]. When conventional parallel grid side converter is completely replaced by the SGSC, as illustrated in Fig. 1, the SGSC is responsible for controlling the stator terminal voltage, as well as the DC-link [25].

In the series-DFIG scheme presented in Fig. 1, the SGSC is coupled to the grid by a series transformer and the DFIG operational principles remain the same. As the current flowing through the SGSC and through the stator machine are the same, or proportional to the series transformer relation, the rotor power flow is controlled by the voltage at the SGSC, given by

$$P = U_{\text{series}d} \times I_{sd} - U_{\text{series}q} \times I_{sq} \tag{1}$$

where $U_{\text{series}d}$ and $U_{\text{series}q}$ are the direct and quadrature components of the voltage induced by the transformer connecting the SGSC, and I_{sd} and I_{sq} are the direct and quadrature components of the stator current.

Considering unbalanced operation conditions, the series-DFIG controls can be separated in positive and negative sequences. The controls applied to the positive sequence variables have the objective to maintain the main functions of the DFIG, controlling the active and reactive power output and the dc link voltage. In this paper these controls have the same objective of the positive sequence controls presented in [25–27]. For the negative sequence control, however, it is proposed a new control methodology. While the negative-sequence controls proposed for the series-DFIG focus only on regulating the output voltage of SGSC for maintaining balanced voltages at the machine stator, in this paper it is proposed to inject an unbalanced current into the grid to compensate the voltage unbalance at the PCC. Although this objective has been used for the conventional DFIG configuration, the series-DFIG presents a better performance for such task, once the consequences of the injection of unbalanced currents can be compensated by applying an adequate voltage at the machine stator, using the SGSC. Besides, the series-DFIG scheme allows improving the voltage ride through capability [23].

To sum up, in the control proposed in this paper, the negative sequence control of the RSC has the objective of injecting a negative sequence current through the machine, and the SGSC has the objective of imposing a voltage to the machine stator to minimize the torque oscillations produced by the negative sequence currents flowing through the machine. The models of the series converter and the machine are following described.

2.1. SGSC model

The SGSC is modelled as illustrated in the three-phase diagram of Fig. 2. A RC filter is connected in parallel to the L_c inductance to reduce the high-frequency distortions present in the output of the three-phase IGBT bridge converter. The equivalent circuit shown in Fig. 2(b) allows calculating the voltage in the series transformer (U_{series}) according to the voltage inserted by the IGBT bridge converter (U_{sc}) and to the RLC values. It is worth noting in Fig. 2(a), the series transformer is delta connected and the RC filter is star connected.