Fault Ride-Through of a DFIG Wind Turbine Using a Dynamic Voltage Restorer During Symmetrical and Asymmetrical Grid Faults

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***Abstract*—The application of a dynamic voltage restorer (DVR) connected to a wind-turbine-driven doubly fed induction generator (DFIG) is investigated. The setup allows the wind turbine system an uninterruptible fault ride-through of voltage dips. The DVR can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation as demanded in actual grid codes. Simulation results for a 2 MW wind turbine and measurement results on a 22 kW laboratory setup are presented, especially for asymmetrical grid faults. They show the effectiveness of the DVR in comparison to the low-voltage ride-through of the DFIG using a crowbar that does not allow continuous reactive power production.**

***Index Terms*—Doubly fed induction generator (DFIG), dynamic voltage restorer (DVR), fault ride-through and wind energy.**

I. Introduction

THE INCREASED amount of power from decentralized renewable energy systems, as especially wind energy systems, requires ambitious grid code requirements to maintain a stable and safe operation of the energy network. The grid codes cover rules considering the fault ride-through behavior as well as the steady-state active power and reactive power production. The actual grid codes stipulate that wind farms should contribute to power system control like frequency and voltage control to behave similar to conventional power stations. A detailed review of grid code technical requirements regarding the connection of wind farms to the electrical power system is given in [1]. For operation during grid voltage faults, it becomes clear that grid codes prescribe that wind turbines must stay connected to the grid and should support the grid by generating reactive power to support and restore quickly the grid voltage after the fault.

Among the wind turbine concepts, turbines using the doubly fed induction generator (DFIG) as described in [2] and [3] are dominant due to its variable-speed operation, its separately controllable active and reactive power, and its partially rated power converter. But the reaction of DFIGs to grid voltage disturbances is sensitive, as described in [4] and [5] for symmetrical and unsymmetrical voltage dips, and requires additional protection for the rotor side power electronic converter.

Conventionally, a resistive network called crowbar is connected in case of rotor overcurrents or dc-link overvoltages to the rotor circuit, and the rotor side converter (RSC) is disabled as described in [6], [7] and [8]. But the machine draws a high short circuit current when the crowbar is activated, as described in [9], resulting in a large amount of reactive power drawn from the power network, which is not acceptable when considering actual grid code requirements. Thus, other protection methods have to be investigated to ride-through grid faults safely and fulfill the grid codes.

There are other proposed solutions using additional hardware for fault ride-through of a DFIG using additional hardware like a series dynamic resistance in the rotor in [10] or in the stator in [11] or using a series line side converter (LSC) topology as in [12].

Other approaches focus on limiting the rotor currents during transient grid voltage by changing the control of the RSC in order to avoid additional hardware in the system. The RSC can be protected by feedforward of the faulty stator voltage [13], by considering the stator flux linkage [14] or by using the measured stator currents as reference for the rotor current controllers [15]. Other publications focus on the improved performance during unsymmetrical grid voltage conditions [16]–[19]. A demagnetizing current is used to protect the converter in [20], but it becomes clear that during deep transient dips, a crowbar activation cannot be avoided, and thus, continuous reactive power control cannot be guaranteed.

If an external power electronic device is used to compensate the faulty grid voltage, any protection method in the DFIG system can be left out. Such a system is introduced in [21] and is called a dynamic voltage restorer (DVR) that is a voltage source converter connected in series to the grid to correct faulty line voltages. The advantages of such an external protection device are thus the reduced complexity in the DFIG system. The disadvantages are the cost and complexity of the DVR. Note that a DVR can be used to protect already installed wind turbines that do not provide sufficient fault ride-through behavior or to protect any distributed load in a microgrid.

Different DVR topologies are compared with respect to rating in power and voltage in [22]. A medium-voltage DVR is described in [23]. Control structures based on resonant controllers to compensate unsymmetrical voltages are presented

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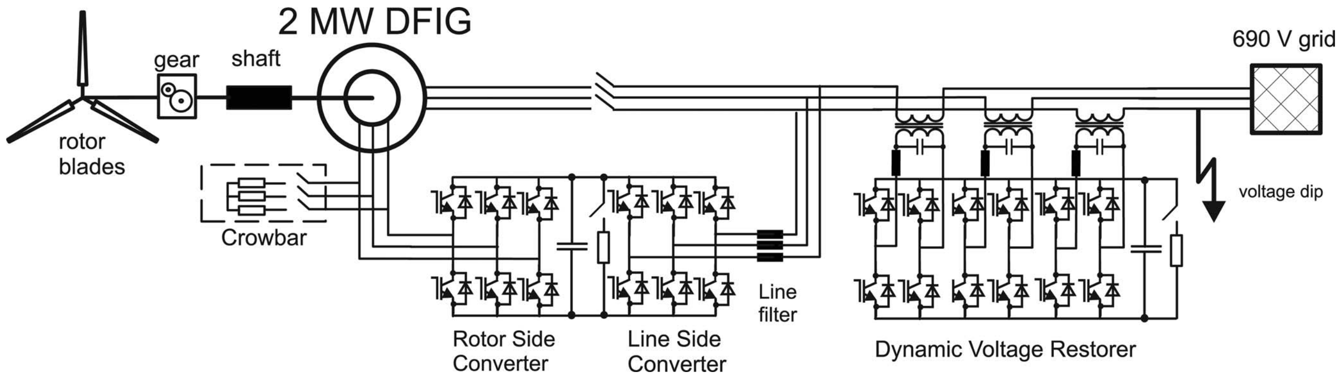

Fig. 1. Schematic diagram of DFIG wind turbine system with DVR.

in [24] and [25]. A DVR is used to provide fault ride-through capability for a squirrel cage induction generator in [26]. A DVR to protect a DFIG wind turbine has been presented in [27], but only symmetrical voltage dips have been investigated, and in [28], but the reactive power is not considered and measurement results do not cover transient grid faults.

In this paper, the application of a DVR that is connected to a wind-turbine-driven DFIG to allow uninterruptible fault ride-through of voltage dips fulfilling the grid code requirements is investigated. The DVR can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation as demanded in actual grid codes. Here, asymmetrical faults are investigated and measurement results under transient grid voltage dips on a 22 kW laboratory setup are presented. First results have been presented in [29], but a detailed analysis of DFIG behavior and DVR control is given here.

The structure is as follows. In Section II, the wind turbine system using a DFIG is described. An analysis of rotor voltage dynamics during transient symmetrical voltage dip and a description of the control structure and conventional crowbar protection are given. In Section III, the DVR electrical system and control using resonant controllers is described. Simulation results for a 2 MW wind turbine in Section IV and measurement results on a 22 kW laboratory test bench in Section V show the effectiveness of the proposed technique in comparison to the low-voltage ride-through of the DFIG using a crowbar. A conclusion closes the analysis.

II. DFIG

The investigated wind turbine system, as shown in Fig. 1, consists of the basic components like the turbine, a gear (in most systems), a DFIG, and a back-to-back voltage source converter with a dc link. A dc chopper to limit the dc voltage across the dc capacitor and a crowbar are included. The back-to-back converter consists of a RSC and a LSC, connected to the grid by a line filter to reduce the harmonics caused by the converter. A DVR is included to protect the wind turbine from voltage disturbances. Due to the short period of time of voltage disturbances, the dynamics of the mechanical part of the turbine will be neglected and the mechanical torque brought in by the wind is assumed to be constant.

A. Rotor Voltage Dynamics

A precise knowledge about amplitude and frequency of the rotor voltage is necessary to design and control the RSC. Therefore, equations for the rotor voltage in normal operation and under symmetrical stator voltage dip are derived in the following as in [4]. Afterwards, the rotor converter rating is taken into account.

From the per-phase equivalent circuit of the DFIG in a static-stator-oriented reference frame, the following stator and rotor voltage and flux equations can be derived:

$$\vec{v}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} \tag{1}$$

$$\vec{v}_r = R_r \vec{i}_r + \frac{d\vec{\psi}_r}{dt} - j\Omega\vec{\psi}_r \tag{2}$$

$$\vec{\psi}_s = L_s \vec{i}_s + L_h \vec{i}_r \tag{3}$$

$$\vec{\psi}_r = L_r \vec{i}_r + L_h \vec{i}_s \tag{4}$$

where $\vec{\psi}$, $\vec{v}$, and $\vec{i}$ represent the flux, voltage, and current vectors, respectively. Subscripts s and r denote the stator and rotor quantities, respectively. $L_s = L_{s\sigma} + L_h$ and $L_r = L_{r\sigma} + L_h$ represent the stator and rotor inductance, L_h is the mutual inductance, R_s and R_r are the stator and rotor resistances, and Ω is the electrical rotor frequency.

By introducing the leakage factor $\sigma = 1 - (L_h^2/L_s L_r)$, the rotor flux can be described in dependence of the rotor current and the stator flux

$$\vec{\psi}_r = \frac{L_h}{L_s}\vec{\psi}_s + \sigma L_r \vec{i}_r. \tag{5}$$

By substituting (5) in (2), an equation for the rotor voltage can be obtained

$$\vec{v}_r = \frac{L_h}{L_s}\left(\frac{d}{dt} - j\Omega\right)\vec{\psi}_s + \left(R_r + \sigma L_r\left(\frac{d}{dt} - j\Omega\right)\right)\vec{i}_r \tag{6}$$

which consists of two parts. The first part is caused by the stator flux $\vec{\psi}_s$ that is given in normal operation by the constantly rotating vector

$$\vec{\psi}_s = \frac{V_s}{j\omega_s} e^{j\omega_s t}. \tag{7}$$