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Low voltage ride through of doubly-fed induction generator connected to the grid using sliding mode control strategy

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ABSTRACT

Wind Energy Conversion System (WECS) based on Doubly Fed Induction Generator (DFIG) connected to the grid is subjected to high transient currents at rotor side and rise in DC-link voltage during voltage sag at stator/grid side. To secure power system operation wind turbines have to meet grid requirements through the Low voltage ride through (LVRT) capability and contribute to grid voltage control during severe situations. This paper presents the modeling and control designs for WECS based on a real model of DFIG taking into account the effect of stator resistance. The non-linear control technique using sliding mode control (SMC) strategy is used to alter the dynamics of 1.5 MW wind turbine system connected to the grid under severe faults of grid voltage. The paper, also discusses the transient behavior and points out the performance limit for LVRT by using two protection circuits of an AC-crowbar and a DC-Chopper which follow a developed flowchart of system protection modes under fault which achieved LVRT requirements through results. The model has been implemented in MATLAB/SIMULINK for both rotor and grid side converters.

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1. Introduction

DFIG has the largest world market share of wind turbine concepts since the year 2002, because of its ability to provide variable speed operation and independent active and reactive control in a cost-effective way. The power production of variable speed wind turbines is higher than fixed-speed turbines, as they can rotate at the optimal rotational speed for each wind speed. Other advantages of the variable speed wind turbines are that they reduce mechanical stresses, they improve power quality, and they compensate for torque and power pulsations. A large number of papers describe the modeling of DFIGs [1–4].

The major drawback of variable speed wind turbines, especially for turbines with DFIGs, is their operation during faults. Faults in the power system even far away from the location of the turbine, can cause a voltage dip at the connection point of the wind turbine. The dip in the grid voltage will result in an increase in the current in stator windings of the DFIG. Because of the magnetic coupling between stator and rotor, this current will also flow in the rotor circuit and the power electronic converter; this can lead to destroy the converter.

The reaction of DFIG to grid voltage disturbances is sensitive, as described in Refs. [5,6] for symmetrical and unsymmetrical voltage dips and requires additional protection for the rotor side power electronic converter. Today, there is a need to control wind power, both in active and reactive powers, and to be able to stay connected to the grid when grid faults happen.

The necessity to establish a grid code was raised due to the fact of the high amount of wind power targeted in Egypt [7]. The low voltage ride through is the most important requirement regarding the wind farm operation that has been recently introduced in the grid codes. It is vital for a stable and reliable operation of power supply networks, especially in regions with high penetration of wind power generation. Faults in the grid can cause a large voltage dip across wide regions and some generation units can be lost as a consequence. SMC is a nonlinear control technique derived from variable structure control system theory which used for torque and pitch control in Ref. [8] and for active and reactive power control in Refs. [9,10]. Ride through of wind turbine with DFIG during voltage dips and using a PI controller is discussed in Ref. [11]. The behavior of the DFIG based wind turbine during grid faults using DC chopper and AC crowbar is explained in Ref. [12]. In Ref. [13] DFIG behavior

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under unsymmetrical voltage dips is studied. A crowbar protection with a stator current feed-back solution is used in Ref. [14]. Improved grid voltage control strategy is discussed in Ref. [15].

In our work, contrary to the previous work carried out on the DFIG where the researchers always neglect the stator resistance to facilitate its control, this resistance was considered in order to return the system studied near to reality. This paper presents LVRT of DFIG connected to the grid using the SMC strategy without/with an active AC crowbar and DC-Chopper circuits that follow a developed flowchart of system protection modes under fault.

2. Grid code requirements

Recent grid codes require wind farms to remain connected and support the grid during and after a fault. They must withstand voltage dips of a certain percentage of the normal voltage for the specified time durations, as shown in the LVRT voltage–time profiles of Fig. 1. Disconnection is not allowed above the borderline and the turbine stay connected even when the voltage at the point of common coupling drops to zero. Below the border line wind turbines are not required to contribute the grid and they can be tripped by circuit breakers after a 150 ms delay.

In Fig. 1, region 1 indicates no tripping and WECS stay connected to the grid even the voltage of Point of Common Coupling to the grid (PCC) dropped to zero. Region 2 indicates tripping of WECS.

3. Doubly fed induction generator

DFIG is currently the most widely used types of electrical generators for wind turbine systems in the Megawatt range [4]. Schematic diagram of on a grid connected DFIG is shown in Fig. 2.

A synchronous rotating d–q reference frame is used to model the DFIG with the direct -axis oriented along the stator flux position. In this way, decoupled control between the electrical torque and the rotor excitation current is obtained. The reference frame is rotating with the same speed as the stator voltage.

The voltages equations are [3]:

$$v_{qs} = R_s I_{qs} + \frac{d\lambda_{qs}}{dt} + (w_s \lambda_{ds}) \tag{1}$$

$$v_{ds} = R_s I_{ds} + \frac{d\lambda_{ds}}{dt} - (w_s \lambda_{qs}) \tag{2}$$

$$v_{qr} = R_r I_{qr} + \frac{d\lambda_{qr}}{dt} + (w_s - w_r)\lambda_{dr} \tag{3}$$

$$v_{dr} = R_r I_{dr} + \frac{d\lambda_{dr}}{dt} - (w_s - w_r)\lambda_{qr} \tag{4}$$

where w_s is the rotational speed of the synchronous reference frame, w_r is the generator rotor speed. The flux linkages are given by:

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \tag{5}$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \tag{6}$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \tag{7}$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \tag{8}$$

$$\lambda_{qm} = L_m (i_{qs} + i_{qr}) \tag{9}$$

$$\lambda_{dm} = L_m (i_{ds} + i_{dr}) \tag{10}$$

where L_s, L_r, and L_m are the stator inductance, rotor inductance and mutual inductances, respectively. The stator active and reactive power can be expressed as:

$$P_s = \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \tag{11}$$

$$Q_s = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \tag{12}$$

And the active and reactive rotor powers are given by

$$P_r = \frac{3}{2}(v_{dr} i_{dr} + v_{qr} i_{qr}) \tag{13}$$

$$Q_r = \frac{3}{2}(v_{qr} i_{dr} - v_{dr} i_{qr}) \tag{14}$$

The electromagnetic torque equation is given by:

$$T_e = \frac{3p}{4}\frac{L_m}{L_s}(\lambda_{qs}\, i_{dr} - \lambda_{ds}\, i_{qr}) = \frac{3p}{4} L_m (i_{qs}\, i_{dr} - i_{ds}\, i_{qr}) \tag{15}$$

where p is the pole number.

4. Sliding mode controller

SMC is a nonlinear control technique derived from Variable Structure Control (VSC) system theory and developed by Vladim

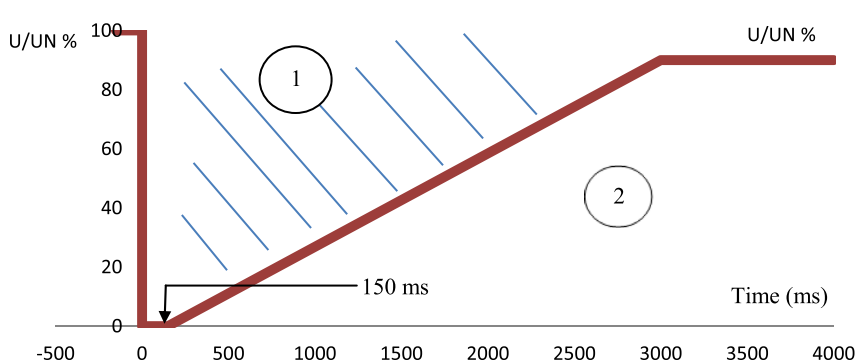

Fig. 1. LVRT requirements of Egypt grid code.

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