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# Detailed study of DFIG-based wind turbines to overcome the most severe grid faults

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ABSTRACT

This paper studies the effects of voltage sags caused by faults on doubly-fed induction generators to overcome grid faults. A wide range of sag duration and depth values is considered. It is observed that sag duration influence is periodical. Sag effects depend on duration and depth and on the fault-clearing process as well. Two approaches of the model are compared: the most accurate approach, *discrete sag*, considers that the fault is cleared in the successive natural fault-current zeros of affected phases, leading to a voltage recovery in several steps; the least accurate approach, *abrupt sag*, considers that the fault is cleared instantaneously in all affected phases, leading to a one-step voltage recovery. Comparison between both sag models reveals that the fault-clearing process smoothes sag effects. The study assumes that the rotor-side converter can keep constant the transformed rotor current in the synchronous reference frame, thus providing insights into wind turbine fault ride-through capability. The voltage limit of the rotor-side converter is considered to show the situations where the rotor current can be controlled. Finally, a table and a 3D figure summarizing the effects of the most severe grid faults on the rotor-side converter to overcome the most severe faults are provided.



## Introduction

According to current transmission system operator grid codes, modern wind turbines (WTs) must achieve fault ride-through capability (i.e., they must not disconnect from the grid when a sag occurs, ensuring electricity supply continuity [1]), and they also must contribute to the system stability during and after the fault clearance by means of the active and reactive current during and after the event.

Doubly-fed induction generator (DFIG)-based WT is the most common concept for WT energy systems [2]. This concept has a high susceptibility to voltage sags. Most studies on DFIGs exposed to sags deal with their control under such disturbances. However, few papers concern the most severe grid fault conditions that can damage the rotor-side converter ([3,4] are examples for symmetrical and unsymmetrical sag events, respectively).

In [5], the authors developed an analytical model for DFIGs exposed to sags. In this model, the rotor-side converter is protected against large over currents caused by sags by a simple control strategy: the rotor current in the synchronous reference frame is kept constant at its pre-fault steady-state value during the entire transient. This control strategy also maintains DFIG controllability as established in current grid codes (i.e. not only to stay connected during the fault, but also draw active and reactive current during and after the fault). As the model is analytical, it allowed a large number of scenarios to be easily studied. The voltage limit of the rotor-side converter was also contemplated in the study.

The present paper is a continuation of the above work. DFIGs under voltage sags are exhaustively studied by considering a wide range of sag duration and depth values, and the situations where the rotor current can be controlled are analyzed. The impact of voltage recovery on DFIGs is also investigated. It is observed that sag effects are smoothed when sags are modeled discrete (sags modeled with a voltage recovery in several steps). The simulations are carried out with Matlab. The results provide insights into the fault ride-through capability of DFIG-based WT in order to overcome the most severe grid faults, whose effects are summarized in a table and a 3D figure.

## Voltage sag modeling

In this paper, voltage sags are characterized by duration ($\Delta t$), depth ($h$), fault current angle ($\psi$), typology and fault-clearing

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process modeling [6,7]. Note that the sag depth ($h$) for the symmetrical sags is the remaining voltage with respect to the pre-fault (nominal) voltage. The sag depth in the unsymmetrical sags is defined by a simple voltage divider on the sequence circuits in radial feeders, as detailed in [6].

According to [7] grid faults can be fully cleared in different ways. All the possibilities are classified into fourteen cases, denoted as $A_1$, $A_2$, $A_3$, $A_4$, $A_5$, B, C, D, $E_1$, $E_2$, $F_1$, $F_2$, $G_1$ and $G_2$. As DFIG stator windings are isolated wye or delta connected, the grid zero-sequence voltage has no influence on DIFG behavior. Consequently, this paper only contemplates the following voltage sags: $A_1$, $A_2$, $A_4$, $A_5$, C, D, $F_1$, $F_2$, $G_1$ and $G_2$, which are shown in Table 1.

As faults are cleared by the circuit breaker in the natural fault-current zeros, unsymmetrical faults involving two fault currents (i.e., 1-phase-to-ground or 2-phase faults) are cleared instantaneously (or abruptly) in all affected phases. This is the case of sag types C and D, which can be indistinctly modeled as abrupt or discrete sags.

In contrast, symmetrical or unsymmetrical faults involving three fault currents (i.e., 3-phase faults, 3-phase-to-ground faults or 2-phase-to-ground faults) are cleared in two or three steps, leading to a discrete voltage recovery. Furthermore, these faults can be fully cleared in different ways, resulting in four discrete symmetrical sag types ($A_1$, $A_2$, $A_4$ and $A_5$) and four discrete unsymmetrical sag types ($F_1$, $F_2$, $G_1$ and $G_2$).

Table 1 also shows the evolution of the events during voltage recovery according to [7]. For example, a sag of type $A_4$ is an event composed of a sag $A_a$ (symmetrical with respect to phase a) during the fault, which evolves into a sag $F_{2a}$ (symmetrical with respect to phase a) after the first voltage recovery, and later into a sag $C_b^*$ (symmetrical with respect to phase b) after the second voltage recovery. Note that faults caused by sags C and D are cleared in one step, as said previously.

## DFIG-based WT characteristics

The chosen 2 MW DFIG-based WT is described in [5]. The following three WT operating points are studied ($s$ being the mechanical slip):

(1) Point 1: rated power and $s = -0.27$.
(2) Point 2: 0.5 times the rated power and $s = -0.09$.
(3) Point 3: 0.1 times the rated power and $s = 0.33$.

## DFIG exposed to voltage sags

### *DFIG dynamic equations*

The DFIG dynamic equations written in transformed variables, using the *Ku* transformation [8] and considering the motor sign conversion, are

$$\begin{aligned} v_{sf} &= [R_s + L_s(p + j\omega_s)]i_{sf} + M(p + j\omega_s)i_{rf} \\ v_{rf} &= [R_r + L_r(p + js\omega_s)]i_{rf} + M(p + js\omega_s)i_{sf} \\ T_m &= 2\wp M \mathrm{Im}(i_{sf}i_{rf}^*) \quad s = (\omega_s - \wp\omega_m)/\omega_s, \end{aligned} \tag{1}$$

where subscripts s and r stand for the stator and the rotor, subscript f stands for the *forward* component of the transformed variable, $\wp$ is the number of pole pairs, $p$ is the time differential operator d/d$t$, $T_m$ is the electromagnetic torque, $s$ is the mechanical slip, $\omega_m$ is the generator speed and $\omega_s = 2\pi f_s$ is the pulsation of the stator voltages ($f_s$ is the frequency of the stator voltages, and $T = 1/f_s$ is the period). Note that all rotor magnitudes in (1) are referred to the stator.

### *DFIG control strategies during voltage sags*

The DFIG behavior during a voltage sag is influenced by two main topics. On the one hand, large rotor currents which cannot be tolerated by the rotor converter are produced during and after the event [9]. On the other hand, current grid codes require to the DFIG to remain connected to the grid, with specific control of the active and reactive currents during and after the fault [3]. Three philosophies can be adopted for the DFIG strategy design:

(1) To disconnect the wind turbine from the grid.
(2) To use a crowbar: a set of resistors short-circuits the machine's rotor. The DFIG remains connected to the grid but it cannot be controlled, as its rotor is short-circuited.
(3) To ensure electricity supply continuity by means of a control strategy in the rotor converter: the DFIG remains connected to the grid and the rotor converter keeps working. However, the philosophy of control during the sag is not a trivial topic and there are very different strategies that can be adopted, depending on the goal to be achieved ([10] compares different control strategies, while [11,12] detail refined control philosophies). The control strategies can be summarized into two types:
   - To reduce the rotor current: it can be suppressed during the sag [13] (thus it has the same problem as the crowbar), or it can be reduced up to a certain value [14]. Another option would be to maintain the pre-event rotor current, as in [15,16].
   - To reduce the rotor voltage [17,18]: in this case it is possible to reduce or damp the stator and the rotor fluxes.

The main problem when using a control strategy is the appearance of large rotor voltage peaks (when controlling the rotor current) or large rotor current peaks (when controlling the rotor voltage) that appear after voltage recovery (see Section 'Comments about the proposed control strategy' for more details). However, these peaks are smoothed when considering the discrete model for the sag. This is an interesting topic, as there are no studies in the literature regarding DFIG-based WTs under voltage sags considering the fault-clearing process.

I should also be noted that the different control strategies result in different DFIG behaviors, with their own strengths and weaknesses. Thus, the use of one or another control philosophy depends on the goal to be achieved. In the present paper it is assumed that the transformed rotor current is kept constant in the synchronous reference frame in order to protect the rotor-side converter from the large rotor current peaks.

### *Proposed current control strategy*

To study DFIG behavior under voltage sags, the next two assumptions are made:

(1) The rotor-side converter can keep constant the rotor current in the synchronous reference frame, $i_{rf}$, at its pre-fault steady-state value. Moreover, the control is assumed ideal, which means that the controlled variable is adjusted instantaneously to satisfy the set point requirement, i.e., $i_{rf}$ is kept constant throughout the event. It should be noted that the current control loop bandwidth has, in practice, a finite value. However, the authors have considered an ideal control as the first approximation to study the problem. This approach could be considered an idealization of the control strategy used in [15,16], where an hybrid current controller is proposed: the standard PI current controller for non-faulted behavior and a hysteresis current controller