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Robust Active Disturbance Rejection Control for LVRT capability enhancement of DFIG-based wind turbines

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ABSTRACT

This article presents the development of a strategy to enhance the Low-Voltage Ride-Through capability (LVRT) of Doubly Fed Induction Generator (DFIG)-based Wind Turbines (WTs). The developed control scheme proposes a trajectory generation system and a high-performance rotor current controller. First, the rotor current trajectories are obtained according to the grid codes requirements. These codes introduce suitable values for the electromagnetic torque and the active and reactive power during operation in normal and fault modes. A detailed analysis of controllability and stability aims to find out how to pair the control inputs and the controlled outputs according to the suggested operation conditions. As a result, a comprehensive study of the required rotor current trajectories to enhance the LVRT capability is developed. Second, the design of the rotor current controller is based on Active Disturbance Rejection Control (ADRC) approach. This controller accomplishes two main objectives: (1) it guarantees a robust tracking of the proposed trajectories, despite uncertainties, disturbances and symmetrical and asymmetrical faults in the grid; and (2) it keeps the rotor voltages and currents in their allowed ratings. Finally, the proposed scheme and the theoretical analysis are validated with simulation studies and laboratory tests.

1. Introduction

Several efforts have been made for the integration of renewable energies into the main power system, in order to meet the demand of reliable and clean electricity generation. For example, the integration of Wind Turbines (WTs), which convert wind energy into electrical power, has increased in the recent years (Liserre, Cardenas, Molinas, & Rodriguez, 2011). As more WTs have been connected to the grid, its requirements for the integration of renewable energy systems are more stringent on the stability concerns of the main power system.

One of the most challenging requirements in grid integration through WT is the Low-Voltage Ride-Through (LVRT) capability, which can be described in three aspects. First, WTs should remain connected during grid voltage dips of short duration. Second, WTs should provide reactive power to support the grid voltage recovery. And third, after the fault clearance, the delivery of active power should be restarted (Mohseni & Islam, 2012; Tsili & Papathanassiou, 2009).

Regarding the first aspect, the voltage profiles are usually depicted in grid codes through descriptions of the depth and duration of a voltage dip at which wind turbines are not allowed to be disconnected. For instance, the German grid codes require that the WTs ride through zero-voltage faults within 150 ms. The WTs should remain connected to the main power system when the voltage levels at the stator terminal and the fault duration are above the curve of Fig. 1(a) (shaded area). In addition, the grid codes state that the WTs should supply reactive power during the voltage dips. WTs are required to contribute to the voltage restoration of the power system by injecting the maximum possible reactive current during the fault.

The most common grid short-circuit faults in a three-phase system can be categorized into four types: three-phase-to-ground, single-phase-to-ground, phase-to-phase, and two-phase-to-ground (Zeng, Nian, & Zhou, 2010). These types are shown in Fig. 2. In addition, the magnitude of its positive and negative sequences can be parameterized by a single parameter, κ, which takes values between 0 and 1. κ also parameterizes the depth of the fault as shown in Fig. 2. These are the fault scenarios that will be considered during this work because the reactive power requirements may differ in the grid fault types. For instance, in Germany, the minimum reactive current under symmetrical fault is 1.0 p.u.; while under asymmetrical faults, the minimum required reactive current is

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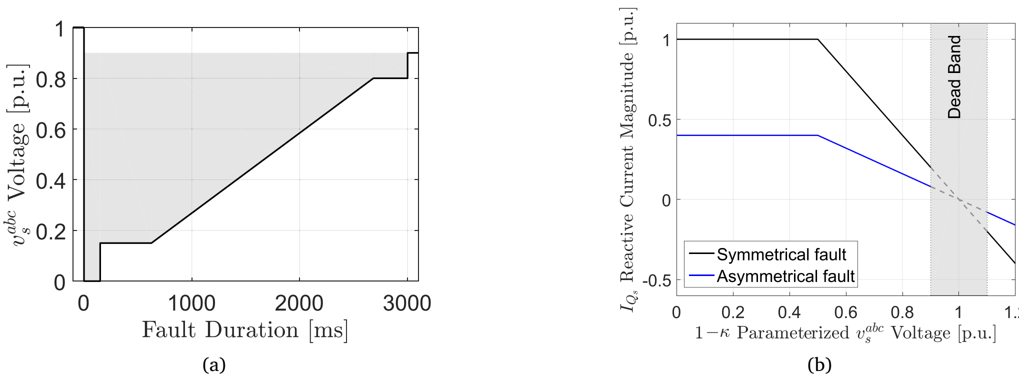
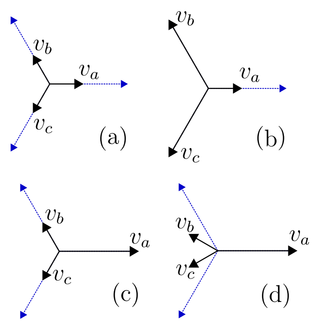


Fig. 1. (a) Voltage profile of the LVRT requirements for WT according to grid codes. (b) Reactive Current requirements for WT according to grid codes (Mohseni & Islam, 2012; Netz GmbH, 2006; Tsili & Papathanassiou, 2009).



Fault Type	V_1	V_2
(a)	$1-\kappa$	0
(b)	$1-\kappa/3$	$\kappa/3$
(c)	$1-2\kappa/3$	$\kappa/3$
(d)	$1-\kappa/2$	$\kappa/2$

Fig. 2. Values per unit of positive (V_1) and negative (V_2) sequence magnitudes of grid voltage during typical voltage fault types in three-phase systems: (a) three-phase-to-ground, (b) single-phase-to-ground fault, (c) two-phase-to-ground fault, (d) phase-to-phase fault.

only 0.4 p.u. Fig. 1(b) shows that the reactive current magnitude I_{Q_s} requirement for WTs is proportional to the depth of the voltage dip κ at the stator terminals. Note that there is a dead band of $\pm 10\%$, where it is considered that the system is still operating at normal conditions.

Doubly Fed Induction Generator (DFIG)-based WT with partially rated power electronics is still the most widely used in Variable Speed Wind Turbine (VSWT) systems. The main reasons are its high efficiency, variable speed operation, as well as the use of converters with partial capacity that enables independent control on active and reactive power. However, the major drawback of the DFIG-based WT is that it is extremely susceptible to grid faults and grid voltage disturbances because the stator of the DFIG is directly connected to the grid, and thus, it is difficult to fulfill LVRT requirements (Jadhav & Roy, 2013). As the stator terminals of the DFIG are directly connected to the main power system, the sudden voltage change induced by the grid faults, either balanced or unbalanced, will result in large current and voltage transients. Moreover, a negative sequence component that makes the system conditions even worse will also appear under unbalanced faults (Marques & Sousa, 2012).

For DFIG-based WTs, the main constraint for riding-through serious grid faults is the limited power electronics rating, because the rotor electromotive force (EMF) usually far exceeds the DC-Bus voltage under a serious grid fault (Lima, Luna, Rodriguez, Watanabe, & Blaabjerg, 2010; López, Sanchis, Roboam, & Marroyo, 2007). In that case, the control system could saturate and lose controllability. In addition to the demanding requirements, DFIG-based WTs face multiple issues during the LVRT process, such as overcurrent in power converters, overvoltage of DC-Bus and torque oscillation that reduces the gearbox duty life (da Costa, Pinheiro, Degner, & Arnold, 2011; Ling & Cai, 2013). Consequently, advanced control designs for DFIG-based WTs and for the development of new hardware equipment in the system are necessary to enable the wind turbine to fulfill all these requirements.

A large number of hardware and control strategies have been proposed to enhance LVRT capability. On the one hand, among hardware solutions, the use of rotor crowbar methods is the preferred scheme adopted by manufacturers (Lima et al., 2010; Rahimi & Parniani, 2010). This method is able to protect the power electronics of the system. However, its major disadvantage is that the Voltage Source Converter (VSC) is isolated from the system when the crowbar circuit is triggered, thus, the DFIG-based WTs is no longer under control. Additional hardware solutions include: virtual resistances (Hu, Lin, Kang, & Zou, 2011), energy capacitor systems (Muyeen et al., 2009), switch-type fault current limiter (Guo et al., 2015), bridge-type fault current limiter (Rashid & Ali, 2017), energy storage systems (Hossain, Pota, & Ramos, 2012; Rahim & Nowicki, 2012), and dynamic voltage restorer systems (Ibrahim, Nguyen, Lee, & Kim, 2011; Ramirez, Martinez, Platero, Blazquez, & de Castro, 2011). However, the use of additional hardware is an unattractive solution, because it increases the cost and worsens the reliability.

On the other hand, LVRT solutions based on control theory have also been proposed. For instance, Liang, Qiao, and Harley (2010) and Zhu, Zou, Zhou et al. (2017) propose a feed-forward current control scheme for the VSCs, by adding feed-forward compensation terms to the outputs of the conventional vector control (VC). The use of classical flux-oriented VC techniques has proven to have an acceptable performance for the accomplishment of the basic grid code requirements. However, these classical techniques have showed to be highly susceptible to actuator saturation, system parameter variations, disturbances and unmodeled dynamics.

Additional studies have proposed different ways to generate rotor current trajectories to enhance the LVRT capability. For instance, Abdelrahem, Mobarak, and Kennel (2016), Yang, Xu, Ostergaard, Dong, and Wong (2012) and Xie et al. (2013) propose to store temporarily part of the captured wind energy during grid faults in the rotor inertia and then release the excessive energy of the rotor to the grid. However, in