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Research Article

Second-order sliding mode control for DFIG-based wind turbines fault ride-through capability enhancement

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ABSTRACT

This paper deals with the fault ride-through capability assessment of a doubly fed induction generator-based wind turbine using a high-order sliding mode control. Indeed, it has been recently suggested that sliding mode control is a solution of choice to the fault ride-through problem. In this context, this paper proposes a second-order sliding mode as an improved solution that handle the classical sliding mode chattering problem. Indeed, the main and attractive features of high-order sliding modes are robustness against external disturbances, the grids faults in particular, and chattering-free behavior (no extra mechanical stress on the wind turbine drive train).

Simulations using the NREL FAST code on a 1.5-MW wind turbine are carried out to evaluate ride-through performance of the proposed high-order sliding mode control strategy in case of grid frequency variations and unbalanced voltage sags.

1. Introduction

An increasing number of power system operators have implemented technical standards known as *grid codes* that wind turbines must meet when connecting to the grid [1,2]. Generally, these grid codes requirements cover many topics such as voltage operating range, power factor regulation, frequency operating range, grid support capability, and low fault ride-through capability. Indeed, grid codes dictate FRT requirements. LVRT capability is considered to be the biggest challenge in wind turbines design and manufacturing technology [3]. LVRT requires wind turbines to remain connected to the grid in the presence of grid voltage sags.

The DFIG is one of the most frequently deployed large grid-connected wind turbines. Indeed, when compared with the full-scale power converter WT concept, the DFIG offers some advantages, such as reduced inverter and output filter costs due to low rotor- and grid-side power conversion ratings (25–30%) [4]. However, DFIG-based WTs are very sensitive to grid disturbances, especially to voltage dips [5].

In this context, this paper proposes to address the FRT problems using a so-called active method achieving FRT with no additional devices. The goal is to control rotor voltages and currents, to reduce the rotor overvoltages and/or overcurrents, and therefore avoid the crowbar use/activation in order to keep full DFIG control at all times to meet the FRT requirements. The implementation of classical flux-oriented vector control techniques (PI controllers) has been proven to work well for the accomplishment of the initial grid code requirements [6–9]. But, this kind of control could be easily saturated when dealing with substantial sag. Moreover, it is sensitive to the generator parameters and other phenomena such as disturbances and unmodeled dynamics [10,11]. In particular, [10] gives a critical review of control methods for LVRT compliance with DFIG. This state-of-the-art review suggests the need of robust and nonlinear controller. A robust one has been proposed in [12], claiming full control in all LVRT cases. However, this was achieved with an oversized converter to accommodate rotor overvoltages and full rotor current control. It is therefore suggested that sliding mode control is a solution of choice to the FRT problem [13].

Therefore and in this particular context, this paper proposes the use of high-order sliding mode control as an improved solution that handles the classical sliding mode chattering problem and particularly avoids using additional devices and converter oversizing. Indeed, the main and attractive features of HOSMs are robustness against

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Nomenclature

WT	wind turbine
DFIG	doubly fed induction generator
FRT	fault ride-through
LVRT	low-voltage ride-through
HOSM	high-order sliding mode
SOSM	second-order sliding mode
MPPT	maximum power point tracking
v	wind speed (m/s)
ρ	air density (kg/m^3)
R	rotor radius (m)
P_a	aerodynamic power (W)
T_a	aerodynamic torque (Nm)
λ	tip speed ratio
$C_p(\lambda)$	power coefficient
ω	wind turbine rotor speed (rad/s)

T_g	generator electromagnetic torque (Nm)
J	turbine total inertia (kg m^2)
K	turbine total external damping (Nm/rad s)
d, q	synchronous reference frame index
s, (r)	stator (rotor) index
V (I)	voltage (current)
P (Q)	active (reactive) power
ϕ	flux
T_{em}	electromagnetic torque
R	resistance
L (M)	inductance (mutual inductance)
σ	leakage coefficient, $\sigma = 1 - M^2/L_sL_r$
θ_r	rotor position
ω_r (ω_s)	angular speed (synchronous speed)
s	slip
p	pole pair number

external disturbances (grid faults) and chattering-free behavior (no extra mechanical stress on the drive train) [14–16]. The proposed control strategy combines an MPPT using a second-order sliding mode for the DFIG control [17,18]. The proposed work is based on [17,18] philosophy (high-order sliding mode). In the case of [18], the control is on the turbine with a specific controller. In the case of [17], the control is on the DFIG as in this paper. However, this paper contribution is on the design of the second-order sliding mode controller based on the supertwisting algorithm that takes into account grid disturbances, in addition to the optimal power extraction [19]. This strategy presents attractive features such as chattering-free behavior, finite reaching time, robustness and unmodeled dynamics (generator and turbine). To check the overall control strategy ride-through performance, simulations using the NREL FAST code on a 1.5-MW wind turbine are carried out in case of grid frequency variations and unbalanced voltage sags.

2. Grid-code requirements

Grid-code requirements typically refer to large wind farms connected to the transmission system, rather than smaller stations connected to the distribution network. These new grid codes stipulate that wind farms should contribute to power system control (frequency and also voltage), much as the conventional power stations, and emphasize wind farm behavior in case of abnormal operating conditions of the network (such as in case of voltage dips). The most common requirements include FRT capability, extended system voltage and frequency variation limits, active power regulation, and frequency control, as well as reactive power/power factor and voltage regulation capabilities [1,2]. Grid codes main requirements regarding the addressed faults are given below.

2.1. Frequency operating range

Wind power plants are required to run continuously within typical grid frequency variations between 49.5 Hz and 50.5 Hz. Fig. 1 gives an example of frequency–grid voltage variations [1].

2.2. Low voltage ride-through

Grid codes invariably require that large wind farms must withstand voltage sags down to a certain percentage of the nominal voltage and for a specified duration. Such constraints are known as LVRT requirements. They are described by a voltage versus time characteristic, denoting the minimum required immunity of the wind power station to the system voltage sags (Fig. 2) [1].

3. Wind turbine modeling

The wind turbine modeling is inspired from [17]. In the following, the wind turbine components models are briefly described.

3.1. Turbine model

In this case, the aerodynamic power captured by the wind turbine is given by

$$P_a = \frac{1}{2}\pi\rho R^2 C_p(\lambda) v^3 \tag{1}$$

where

$$\lambda = \frac{R\omega}{v} \tag{2}$$

The rotor power (aerodynamic power) is also defined by

$$P_a = \omega T_a \tag{3}$$

The following simplified model is adopted for the turbine (drive train) for control purposes.

$$J\dot{\omega} = T_a - K\omega - T_g \tag{4}$$

3.2. DFIG model

The control system is usually defined in the synchronous $d-q$ frame fixed to either the stator voltage or the stator flux. For the proposed control strategy, the generator dynamic model written in a synchronously rotating frame $d-q$ is given by

$$\begin{cases} V_{sd} = R_s I_{sd} + \frac{d\phi_{sd}}{dt} - \omega_s \phi_{sq} \\ V_{sq} = R_s I_{sq} + \frac{d\phi_{sq}}{dt} + \omega_s \phi_{sd} \\ V_{rd} = R_r I_{rd} + \frac{d\phi_{rd}}{dt} - \omega_r \phi_{rq} \\ V_{rq} = R_r I_{rq} + \frac{d\phi_{rq}}{dt} + \omega_r \phi_{rd} \\ \phi_{sd} = L_s I_{sd} + M I_{rd} \\ \phi_{sq} = L_s I_{sq} + M I_{rq} \\ \phi_{rd} = L_r I_{rd} + M I_{sd} \\ \phi_{rq} = L_r I_{rq} + M I_{sq} \\ T_{em} = pM(I_{rd} I_{sq} - I_{rq} I_{sd}) \end{cases} \tag{5}$$