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DFIG Driven Wind Turbine Grid Fault-Tolerance Using High-Order Sliding Mode Control

Mohamed Benbouzid¹, Brice Beltran¹, Marwa Ezzat^{1,2} and Sylvie Breton¹

Abstract—This research note deals with grid fault-tolerance of a doubly-fed induction generator-based wind turbine using high-order sliding mode control. Indeed, it is proposed to assess the main and attractive features of high-order sliding modes which are robustness against external disturbances (e.g. grid) and chattering-free behavior (no extra mechanical stress on the drive train). Simulations using the NREL FAST code on a 1.5-MW wind turbine are carried-out to evaluate ride-through performances of high-order sliding mode control. **Copyright © 2013 Praise Worthy Prize S.r.l. - All rights reserved.**

Keywords: Wind turbine, doubly-fed induction generator (DFIG), control, second-order sliding mode, grid fault-tolerance.

Nomenclature

WT	=	Wind Turbine;
DFIG	=	Doubly-Fed Induction Generator;
ω_{mr}	=	Wind turbine rotor speed;
T_g	=	Generator electromagnetic torque;
J_t	=	Turbine total inertia (kg m ²);
K_t	=	Turbine total external damping;
V, I, ϕ	=	Voltage, Current, Flux;
T_{em}	=	Electromagnetic torque;
R, L, M	=	Resistance, Inductance, Mutual inductance;
σ	=	Leakage coefficient, $\sigma = 1 - M^2/L_s L_r$;
ω_r, ω_s	=	Angular speed, Synchronous speed;
s, p	=	Slip, Pole pair number.

I. Introduction

Fault ride-through specifications listed in modern transmission and distribution grid codes specify that wind-turbine generators must remain connected to electricity networks at voltage levels well below nominal [1]. Achieving reliable operation at greatly reduced voltage levels is proving problematic. A particular problem is that standard controllers designed for reliable operation around nominal voltage levels will not work as designed during low network voltages that can occur during a fault. A consequence of this is greatly increased currents, which may lead to converter failure. Achieving ride-through requirement for DFIG-based wind turbine is a significant technical issue on which turbine manufacturers are working and for which some control-based solutions are proposed. Therefore, this short communication assesses one of the main features of a sliding mode approach which is robustness against

external disturbances (e.g. grid). In particular, high-order sliding mode control is adopted as it presents attractive features such as chattering-free behavior (no extra mechanical stress), finite reaching time, and robustness with respect to external disturbances (grid) and unmodeled dynamics (generator and turbine) [2].

II. Wind Turbine Modeling Briefly

The turbine modeling is inspired from [2]. In this case, the following simplified model is adopted for the turbine for control purposes.

$$J_t \dot{\omega}_{mr} = T_a - K_t \omega_{mr} - T_g \quad (1)$$

DFIG control system is usually defined in the synchronous d - q frame fixed to the stator flux for a decoupled control. For simplification purposes, the q -axis is aligned with the stator voltage and the stator resistance is neglected. These will lead to

$$\begin{cases} \frac{dI_{rd}}{dt} = \frac{1}{\sigma L_r} \left(V_{rd} - R_r I_{rd} + s \omega_s \sigma L_r I_{rq} - \frac{M}{L_s} \frac{d\phi_{sd}}{dt} \right) \\ \frac{dI_{rq}}{dt} = \frac{1}{\sigma L_r} \left(V_{rq} - R_r I_{rq} - s \omega_s \sigma L_r I_{rd} - s \omega_s \frac{M}{L_s} \phi_{sd} \right) \\ T_{em} = -p \frac{M}{L_s} \phi_{sd} I_{rq} \end{cases} \quad (2)$$

III. DFIG-Based Wind Turbine Control

Setting the reactive power to zero leads to the following rotor reference current.

$$I_{rd_ref} = \frac{V_s}{\omega_s M} \quad (3)$$

The DFIG-based wind turbine control objective is to optimize the wind energy capture by tracking the optimal torque T_{ref} . This control objective can be formulated by the following tracking errors.

$$\begin{cases} e_{I_{rd}} = I_{rd} - I_{rd_ref} \\ e_{T_{em}} = T_{em} - T_{ref} \end{cases} \quad (4)$$

Then we will have

$$\begin{cases} \dot{e}_{I_{rd}} = \frac{1}{\sigma L_r} \left(V_{rd} - R_r I_{rd} + s \omega_s L_r \sigma I_{rq} - \frac{M}{L_s} \frac{d\phi_{sd}}{dt} \right) - \dot{I}_{rd_ref} \\ \dot{e}_{T_{em}} = -p \frac{M}{\sigma L_s L_r} \phi_s \left(V_{rq} - R_r I_{rq} - s \omega_s L_r \sigma I_{rd} - s \omega_s \frac{M}{L_s} \phi_{sd} \right) - \dot{T}_{ref} \end{cases} \quad (5)$$

The proposed second-order sliding mode control approach has been designed using the supertwisting algorithm (6) [2].

$$\begin{cases} \dot{V}_{rd} = y_1 + B_1 \left| e_{T_{em}} \right|^{\frac{1}{2}} \text{Sgn}(e_{T_{em}}) \\ \dot{y}_1 = +B_2 \text{Sgn}(e_{T_{em}}) \\ \dot{V}_{rq} = y_2 - B_3 \left| e_{I_{rd}} \right|^{\frac{1}{2}} \text{Sgn}(e_{I_{rd}}) \\ \dot{y}_2 = -B_4 \text{Sgn}(e_{I_{rd}}) \end{cases} \quad (6)$$

where

$$\begin{cases} B_1 > \frac{\Phi_2}{\sigma L_r}, \quad B_2^2 \geq \frac{4\Phi_1(B_1 + \Phi_1)}{\sigma^2 L_r^2 (B_1 - \Phi_1)}, \\ G_1 = \frac{1}{\sigma L_r} \left(s \omega_s \sigma L_r I_{rq} - \frac{M}{L_s} \frac{d\phi_{sd}}{dt} - R_r I_{rd} \right) - \dot{I}_{rd_ref} \\ \left| \dot{G}_1 \right| < \Phi_1 \\ B_3 > p \frac{M}{\sigma L_s L_r} \Phi_1, \quad B_4^2 \geq \frac{4\Phi_2(B_3 + \Phi_2)}{\sigma^2 L_r^2 (B_3 - \Phi_2)} \\ \left| \dot{G}_2 \right| < \Phi_2 \\ G_2 = -p \frac{M}{\sigma L_s L_r} \phi_s \left(R_r I_{rq} - s \omega_s \sigma L_r I_{rd} - s \omega_s \frac{M}{L_s} \phi_{sd} \right) - \dot{T}_{ref} \end{cases} \quad (7)$$

Figure 1 illustrates the proposed control strategy for a DFIG-based wind turbine [2-3].

IV. Simulation Results using the FAST Code

Numerical validations, using FAST with Matlab-Simulink[®] have been carried out on the NREL WP 1.5-MW wind turbine [3].

In the following, the second-order sliding mode tracking performances (robustness) are assessed during two main grid faults.

IV.1. Frequency Variation

In case of generation loss, the grid frequency falls rapidly. The proposed control strategy has been therefore tested in case of frequency fall from 50 Hz to 48 Hz (Fig. 2). Figure 3 clearly shows that the frequency fall has practically no effect on the torque.

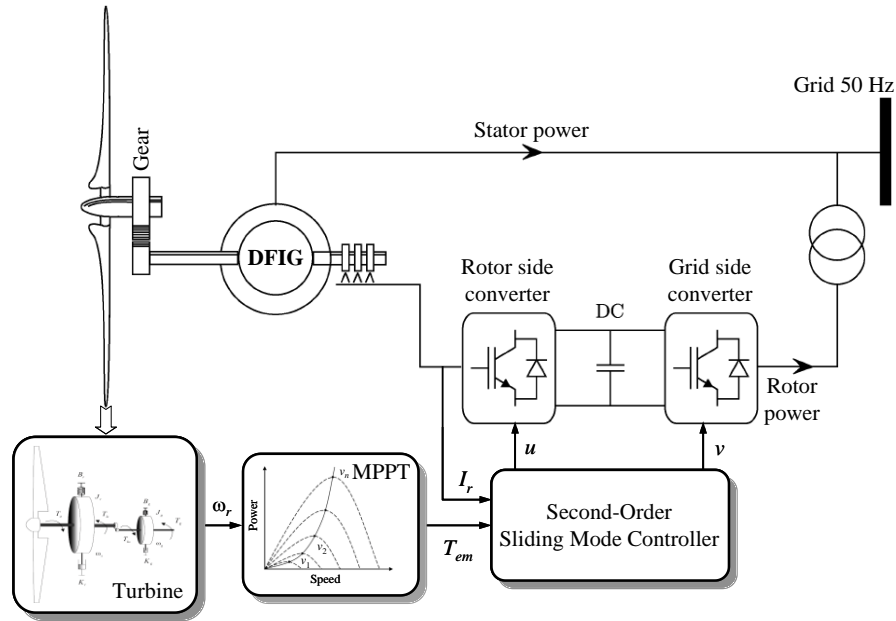


Fig. 1. The proposed control structure.

IV.2. Unbalanced Voltage Sags

When unbalanced sags occur, the main problem is that very high current, torque, and power oscillations appear at double of the electrical frequency, forcing a disconnection.

Figure 5 demonstrates successful ride-through performance using the proposed control technique during the unbalanced voltage sags of Fig. 4. Indeed, an almost constant torque is achieved. Moreover, good tracking performances are also achieved in terms of DFIG rotor current (Fig. 6).

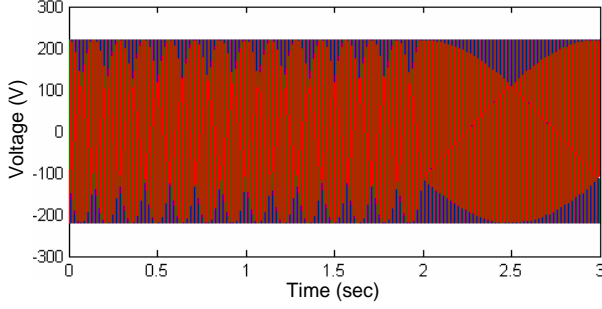


Fig. 2. Grid voltage during a frequency variation.

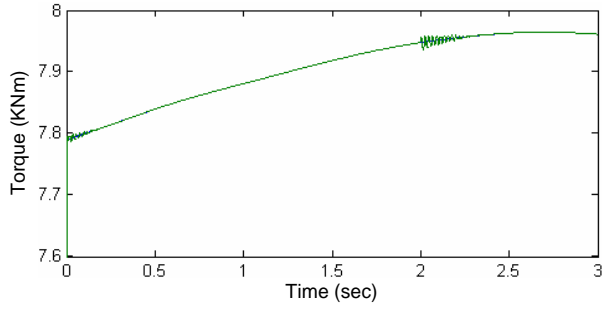


Fig. 3. Torque tracking performance: Reference (green) and real (blue).

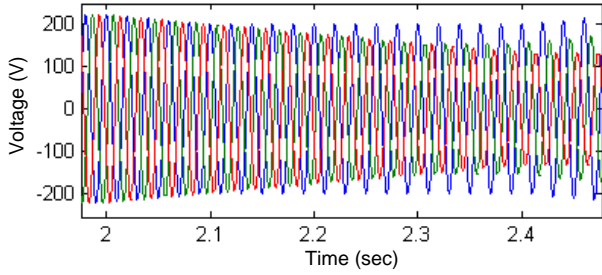


Fig. 4. Grid voltage.

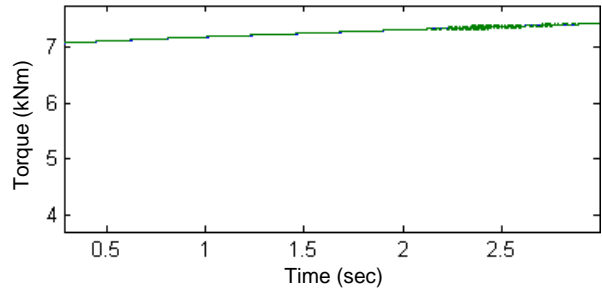


Fig. 5. Torque tracking performance: Reference (blue) and real (green).

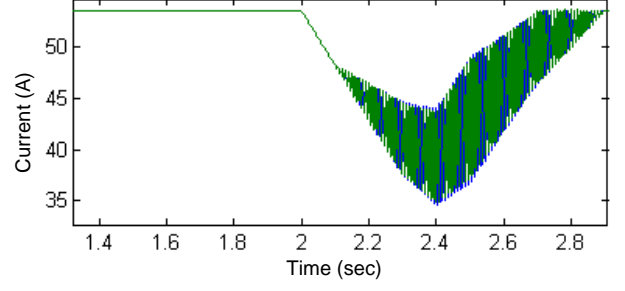


Fig. 6. Current I_{rd} tracking performance: Reference (blue) and real (green).

V. Conclusion

This research note dealt with a second-order sliding mode control of doubly-fed induction-based wind turbine for grid fault-tolerance. Preliminary results in case of frequency variation and voltage unbalance sags show promising successful ride-through performances.

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