Electric Power Systems Research 146 (2017) 258–269

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

A new fault ride-through control for DFIG-based wind energy systems

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ARTICLE INFO

Article history:
Received 21 October 2016
Received in revised form 13 January 2017
Accepted 10 February 2017

Keywords:
Sliding mode control
Second order integral terminal
Wind turbine
Fuzzy control
Voltage sag

ABSTRACT

This paper deals with the design and analysis of a fault ride-through control (FRTC) scheme for a DFIG-based wind turbine. A new Fuzzy Second Order Integral Terminal Sliding Mode Control (FSOITSMC) is designed for the rotor and grid-side converters. The design is further augmented by a series grid side converter (SGSC) in order to avoid DFIG's disconnection from the grid during faulty conditions. The proposed control paradigm was implemented on a DFIG-based wind turbine. Its performance was assessed using DFIG's realistic modes of operation such as normal, sub- and super-synchronous modes. Both symmetrical and unsymmetrical faults were considered to further evaluate the performance of the proposed approach. Simulation results proved the ability of the proposed FRTC scheme in effectively controlling DFIG-based wind turbines under various operating conditions. Despite subjecting the DFIG to various modes of operations and extreme faulty conditions, the over currents of the rotor and stator did not exceed 10%, which is a very good performance compared to existing approaches.

The proposed approach was able to maintain the DFIG's currents and voltages within acceptable ranges, hence preventing damages to the converters during various faulty conditions. Endowing the DFIG with superior ride through capabilities and ensuring its continuous connectivity to the grid even under non-ideal grid voltage conditions are among the positive features of the proposed approach.

1. Introduction

Wind energy generates variable power that is very consistent from year to year but has significant variations over shorter time spans. Hence, it's often used in conjunction with other electric power sources to ensure a reliable supply [1]. Doubly Fed Induction Generators (DFIGs) are quite popular in wind energy generation and distribution systems. They owe this popularity to their high energy transfer capability, flexible control and relatively low cost. To feed the wound rotor, DFIGs typically employ series voltage source converters on both the rotor side (RSC) and grid side (GSC). These later endow the DFIG with additional advantages such as stability and flexible control. However, wind turbine connection to the microgrid has led to new control challenges, such as active and reactive power control and voltage sag mitigation. Classical control techniques, such as the PI-based controllers described in Refs. [1–3], can only provide good performance under ideal grid voltage conditions. They often lead to remarkable swings in the active and reactive powers, the DC-link voltage, and electromagnetic torque under fault conditions [4]. These power swings could damage the electrical and mechanical portions of WTs, and result in its disconnection from the grid.

Sliding Mode Control (SMC) have recently been considered in designing controllers for the series voltage source converters of wind turbine energy systems [5,6]. Although very robust and accurate, standard SMC suffers from two major drawbacks [7]. First, the chattering phenomena resulting from the high frequency control switching, which severely restricts its application to wind power systems since it deteriorates the control performance and excites high frequency oscillations. Second, the requirement of the relative degree of the constraint to be one, which limits its application. To alleviate the above mentioned drawbacks, a number of variants to the standard SMC approach were proposed in the literature [8–11]. Terminal Sliding Mode Control (TSMC) was proposed for the control of high order systems [10]. It replaced linear hyperplanes, typically used in standard SMC, by nonlinear switching manifolds to ensure system state convergence in finite time. However TSMC suffers from poor transient performance [11]. Integral TSMC (ITSMC) was proposed to further improve the performance of the system in the presence of unmatched disturbances. It achieves finite-time convergence while still preserving the robust properties of SMC by adding an integral term to the sliding mode variables [12]. High order sliding mode approaches are capable of successfully allevi-

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http://dx.doi.org/10.1016/j.epsr.2017.02.010
0378-7796/

Nomenclature

PCC	Point of common coupling
LVR	Low-voltage ride-through
d (q)	Direct (quadrature) axis
s (r)	Subscripts for stator (rotor)
α, β	Stationary reference frame
R_g $\left(L_g\right)$	Resistances (inductance) of grid side converter
R_s (L_s)	Resistance (inductance) of stator of DFIG
R_r (L_r)	Resistance (inductance) of rotor of DFIG
M	Mutual inductance between stator and rotor of DFIG
$i_{rdq-ref}$	Reference current of DFIG rotor in the d-q frame
$i_{gdq-ref}$	Reference current of grid side converter of DFIG in the d-q frame
s	Slip
V_r (i_r)	DFIG rotor voltage (current)
V_s (i_s)	DFIG stator voltage (current)
V_g $\left(i_g\right)$	Grid side voltage (current) of DFIG
V_{SE}	Injected compensation voltage by SGSC
ω_r (ω_s)	Mechanical (synchronous) speed of the DFIG
φ_s (φ_r)	Stator (rotor) flux
R_f, L_f, C_f	Resistance, inductance, capacitor of the series inverter filter
e (g)	Abbreviation symbol for rotor (grid) side variable
S (σ)	Surface (manifold) of sliding mode controller
$\alpha_{d,q,\alpha}$, $\beta_{d,q,\beta}$	Positive constants defined in the manifold of sliding mode
K_1, K_2, K_3	Positive constants defined in law control
ξ	Maximum limit of stator flux for unbalance conditions
T_d	Period of damped response signal
$v_{\alpha\beta inj}$	Injected voltage by SGSC in stationary reference frame
$v_{\alpha\beta actual}$	Actual voltages of the grid in stationary reference frame
$v_{\alpha\beta desired}$	Desired voltages for the grid in stationary reference frame
$v_{\alpha\beta inj-dif}$	Reference voltages of the SGSC in the stationary reference frame
ϑ	Overshoot of the lightly damped system

ating the relative-degree restriction and reducing the chattering, thus improving the sliding mode's practical accuracy [13–17].

Voltage sag is a short duration reduction in *rms* voltage which can be caused by a short circuit, overload or starting of electric motors. The voltage sag can affect performance of the DFIG-based wind turbine connected to grid. The voltage sag can damage the DFIG of wind turbines. During the voltage sag, the rotor current increases considerably. This increase is most significant in the initial and final steps of the voltage sag duration. Moreover, the electromagnetic torque and DC-link voltage also experience high fluctuations, resulting in DFIG to be disconnected from grid. Note that deep voltage sag conditions and the resulting large electromagnetic forces cause the RSC to go into over-modulation, leading to loss of rotor current regulation. Hence, the magnitude of rotor and stator currents should be limited, and remain at their acceptable ranges to prevent disconnecting the DFIG from grid. Note that controlling the RSC and GSC alone during grid faults will not prevent WT's disconnection from the grid, especially when the fault magnitude is significant (deep voltage sags). Hence, any ride-through design should be augmented by additional controllers or components to ensure continuous connectivity to the grid regardless of the fault magnitude.

Recently, several ride through approaches have been proposed to mitigate voltage sags and subsequently improve the reliability of wind power generation. The most well-known approach relies on the addition of crowbar circuits [18]. However, this technique leads to the absorption of large values of reactive power during voltage sags, resulting in further aggravating the voltage sag. A nine-switches inverter with two independent output voltage was proposed in Ref. [19] as an alternative to GSC and series converters. However, multi-output inverters increase the voltage stress on the DC link capacitor and lead to losses due to the higher switching frequency in comparison with conventional inverters. Injecting reactive power using parallel reactive elements such as STATCOM was proposed as an alternative. In Ref. [20], a Series Grid Side Passive-Impedance (SGSPI) was considered to control the DFIG during voltage sags. However, the SGSPI approach led to huge spikes in the electromagnetic torque both at the starting and ending point of voltage sag [21]. Series dynamic resistors is another approach which has been applied to keep the stator voltages and rotor currents within acceptable ranges. However, the method is not suitable when the DFIG is expected to inject reactive power to the grid [22]. Moreover, the above mentioned ride through approaches typically fail to keep the voltage across the stator at its pre-fault levels, hence leading to undesirable mechanical and electrical transients in the system.

Using parallel components such as a STATCOM to inject a shunt current can compensate for the voltage unbalance at PCC, hence eliminating the electromagnetic torque oscillation and the stator and rotor current unbalances. However, the total active and reactive power of the DFIG will still carry double-frequency oscillation, which is harmful to the stability of the connected grid. It is worth noting that, in order to reduce the voltage unbalance, it is advisable [23] to use an active series compensator since it can be sized at a limited power value. Using an active parallel compensator on the other hand leads toward bigger capacity. The dynamic voltage resistor (DVR) as an active series compensator was proposed in Refs. [24–26]. However, the complexity in implementing the controllers prevented its wide deployment in wind energy systems. Recently, Series Grid Side Converters (SGSCs) [27,28] were proposed as a ride-through mechanism which mitigates voltage sags by injecting additive voltage to the DFIG to ensure its continuous connectivity to the grid. In Ref. [27], RSC was used to control the negative sequence current injected through the stator, while the SGSC was considered to control the negative sequence stator voltage and minimize the electromagnetic torque oscillations. PI-controllers were used to control the RSC and SGSC under voltage sag conditions. A PI-based controller was proposed in Ref. [28] to limit the high currents of the rotor side converter and provide the stator circuits with the necessary voltage via a series transformer without disconnecting the converter from the rotor or from the grid.

In this paper, a new control approach is proposed for a microgrid connected DFIG-based wind turbine to provide smooth operations during voltage sag conditions while satisfying the recent grid code requirements illustrated in Fig. 1. A fuzzy second order ITSMC (FSOITSMC) is designed to control the RSC and GSC of DFIG installed in microgrid, a fuzzy logic controller is proposed to tune the controller coefficients of sliding mode control approach. To maintain the generator voltage within acceptable ranges and prevent the DFIG from being disconnected from the grid during deep voltage sags, an SGSC is added to the structure. This ensures that the stator and rotor currents keep at their nominal values. The FSOITSMC and Posicast controllers are then proposed to control the SGSC and further improve the performance of the DFIG. This will ensure that the DFIG will not be disconnected from the network and support the grid even during deep voltage sags. The main contributions of this paper are as follows: