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Low and high voltage ride-through of DFIG wind turbines using hybrid current controlled converters

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ABSTRACT

Doubly fed induction generators have been recognized as the dominant technology used in wind generation systems. However, this type of wind generator is very sensitive to the drop/rise in the supply voltage and without efficient "ride-through" strategy, continuous operation of DFIG may fail due to destructive overcurrents in the rotor winding or large overvoltages in the dc-link capacitor. This paper introduces a hybrid current control scheme, implemented in the rotor-side and grid-side converters of DFIG, to enhance low and high voltage ride-through capacities of DFIG-based wind turbines. The proposed control scheme is constituted of two switching strategies integrated with a supervisory control unit: standard PI current controllers for normal operating conditions and vector-based hysteresis current controllers for DFIG protection during severe voltage sag/swell conditions. Time-domain simulation studies are carried out to examine the effectiveness of the proposed ride-through strategy under various types of grid disturbances. It is shown that the proposed controller constrains the rotor current and dc-link voltage within the safety limits of DFIG and as a result, the wind generator can comply with the strict low/high voltage ride-through requirements stipulated by modern grid codes.

1. Introduction

DFIGs have recently become the most dominant technology used in wind energy conversion systems [1]. This promising technology offers many technical/economical advantages compared to other types of wind generators, but suffers from a sheer vulnerability to the grid disturbances, especially to the voltage sag and swell events. In the past, wind generators were allowed to disconnect from the grid during disturbances in order to protect their vulnerable power electronic parts. However, modern grid codes have become more stringent and specify the voltage sag profile for which wind generators must remain connected to the grid. This is commonly referred to as the LVRT requirement [2]. In some countries like Australia, Germany and UK, new grid codes are even more demanding and require wind generators to withstand severe voltage swell profiles, referred to as the HVRT requirement. Fig. 1(a) and (b) shows the practical instants of LVRT and HVRT profiles required in the Spanish and Australian grid codes, respectively [3,4]. Points A, B and C represent the most extreme operating conditions that will be examined in this paper.

Voltage sags have been reported as the most common power quality disturbance experienced in industrial power systems and for this reason, LVRT requirements are included in the majority of grid codes around the world [2]. Therefore, extensive research has been so far reported on the LVRT capability enhancement of DFIGs [5–18]. However, the HVRT behaviour of DFIG-based wind turbines is just an emerging issue which has not been adequately explored in the literature [19].

The early researches on the voltage sag behaviour of DFIGs have identified two major problems that need close attention: (1) overcurrents in the rotor winding and (2) overvoltages in the dc-link capacitor [5,6]. The initial solution to protect the RSC from destructive overcurrents was to place short-circuit at the rotor slip ring terminals via the so called crowbars and then, disconnect the DFIG form the grid [7]. This solution was only acceptable when the wind power constituted an insignificant part of the system generation. Hence, other approaches have been recently proposed to increase the LVRT capacity of DFIGs. The LVRT strategies reported in the literature can be divided into three main categories: (1) placing active crowbars at the RSC terminals [8,9], (2) installing additional converters/dynamic resistors in the DFIG structure [10–12], and (3) modifying the conventional control schemes [13–17]. Active crowbars are proven to be effective under balanced fault conditions, but they cannot assist the DFIG to ride through deep asymmetrical sags

Abbreviations: DFIG, doubly fed induction generator; GSC, grid-side converter; HVRT, high voltage ride-thorough; LVRT, low voltage ride-through; PI, proportional-integral; PLL, phase locked loop; RSC, rotor-side converter; SVM, space vector modulation; THD, total harmonic distortion; VBHCR, vector-based hysterias current regulator.

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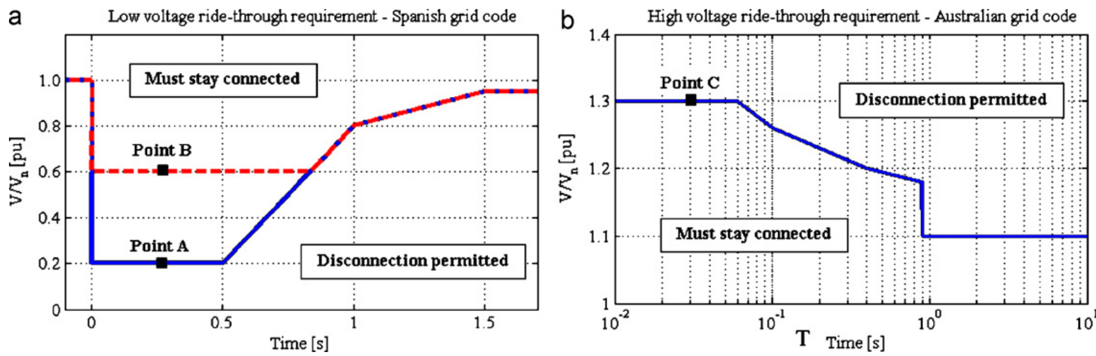

Fig. 1. (a) Spanish LVRT profile (dashed line: two-phase faults, solid line: other types of fault). (b) Australian HVRT profile.

such as phase-to-phase faults (due to the large negative-sequence of the rotor current). The second approach can improve the LVRT capability of DFIGs under various sag conditions, but increases the overall cost and complexity. Finally, modified control schemes have been introduced as the most successful LVRT strategy. These control techniques are typically structured in two main steps: (1) decomposition of the voltage/current signals into the symmetrical components and (2) regulation of the rotor current in two opposite rotating frames, using dual PI current controllers [14–17]. This is however shown that these control schemes suffer from stability problems and very limited control bandwidth, due to the sluggish transient response of PI current controllers and considerable time delay introduced during the decomposition process [17,20]. This will result in degraded transient response of DFIG to voltage sags and consequently, strict grid code regulations cannot be met.

In [21], the issue of overvoltage in the dc-link capacitor of DFIGs is addressed by adopting a modified control scheme in the GSC of DFIGs. The proposed GSC control loop includes a feedback from the instantaneous rotor power, but still uses the conventional PI current controllers. As a result, it suffers from the sluggish transient response and limited LVRT capability similar to [14] and [15].

This paper introduces a new hybrid current controller to improve both LVRT and HVRT capacities of DFIG-based wind turbines. The proposed current controller is constituted of two different switching strategies integrated with a supervisory control unit. Under normal operating conditions, standard PI current controllers (with optimal steady-state response) are used to regulate the output currents of the rotor-side and grid-side converters. However, the PI current controllers have very limited control bandwidth, which is not adequate for low/high voltage ride-through purposes. Therefore, upon detecting a grid disturbance, the supervisory control unit transfers the switching strategy of converters to a VBHCR. This hysteresis-based current controller was originally introduced by the authors for the conventional voltage source converters [22]. It is already shown that the proposed VBHCR can retain the main advantages of the conventional hysteresis method such as very fast transient response and insensitivity to the system parameters variations. This current controller also attains an improved steady-state performance by reducing the average switching frequency of converters. This improvement is crucial to avoid the thermal stability problems in the converters and their associated gate-driving devices. Furthermore, the proposed hysteresis-based method is superior to the predictive current controllers because of its inherent peak current limiting characteristic and simpler control structure [23]. However, long-time operation of VBHCRs should be avoided due to its variable switching frequency and low-order current harmonic distortions. Therefore, the VBHCRs are only activated for short fault periods to mitigate the rotor current oscillations and keep the dc-link voltage within the safety limits of DFIG. Then, the PI current controllers will be reactivated through a re-initialization mechanism.

2. DFIG system modeling

Detailed transient model of DFIG-based wind turbines is studied in [24,25]; therefore, only the most important aspects of model will be presented here. Fig. 2 shows the Γ-form equivalent circuit of the machine used in this paper for the machine modeling [26]. The stator- and rotor-voltage vectors in the arbitrary reference frame are defined as

$$\boldsymbol{V}_{\mathrm{s}} = R_{\mathrm{s}}\boldsymbol{I}_{\mathrm{s}} + \frac{d\lambda_{\mathrm{s}}}{dt} + j\omega \cdot \lambda_{\mathrm{s}} \tag{1}$$

$$\boldsymbol{V}_{\mathrm{r}} = R_{\mathrm{r}}\boldsymbol{I}_{\mathrm{r}} + \frac{d\lambda_{\mathrm{r}}}{dt} + j(\omega - \omega_{\mathrm{r}}) \cdot \lambda_{\mathrm{r}} \tag{2}$$

where 'ω' is the angular speed of the arbitrary frame and subscripts 's' and 'r' distinguish quantities or parameters on the stator and rotor windings, respectively. According to Fig. 2, the stator and rotor flux space vectors can be defined as

$$\lambda_{\mathrm{s}} = L_{\mathrm{m}}(\boldsymbol{I}_{\mathrm{s}} + \boldsymbol{I}_{\mathrm{r}}) = L_{\mathrm{m}}I_{\mathrm{m}} \tag{3}$$

$$\lambda_{\mathrm{r}} = L_{\sigma}\boldsymbol{I}_{\mathrm{r}} + L_{\mathrm{m}}(\boldsymbol{I}_{\mathrm{s}} + \boldsymbol{I}_{\mathrm{r}}) \tag{4}$$

where L_{m} and L_{σ} are the magnetizing and leakage inductances, respectively. Using Eqs. (3) and (4), the rotor flux and stator current can be expressed as

$$\boldsymbol{I}_{\mathrm{s}} = \frac{\lambda_{\mathrm{s}}}{L_{\mathrm{m}}} - \boldsymbol{I}_{\mathrm{r}} \tag{5}$$

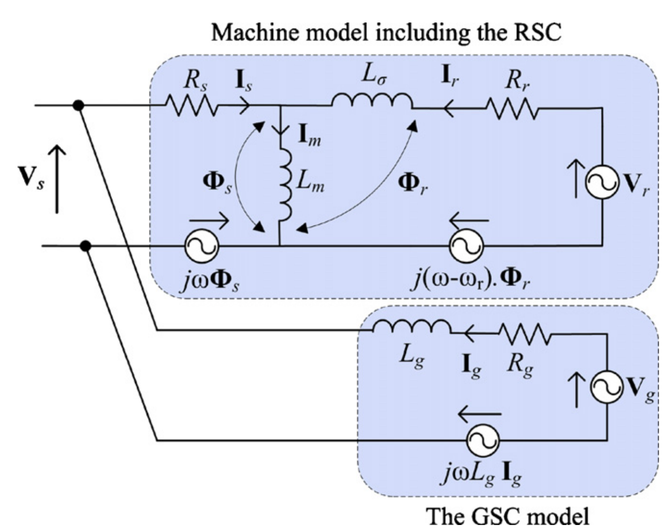

Fig. 2. Conventional Γ-form equivalent circuit of DFIG.