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A SCR crowbar commutated with power converter for DFIG-based wind turbines

Shuying Yang *, Tianbao Zhou, Dengyue Sun, Zhen Xie, Xing Zhang

Hefei University of Technology, School of Electrical Engineering and Automation, Hefei, China

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ABSTRACT

This paper presents an active crowbar, constructed with silicon controlled rectifiers (SCRs), for doubly fed induction generator (DFIG)-based wind turbines to fulfill low-voltage ride-through (LVRT) requirements demanded by grid codes. By this design, not only the active deactivation of the costly IGBT crowbar, replacing the passive crowbar for this ability, can be achieved with the more cost-effective SCRs, but also the reliability of the circuit is strengthened thanking to the high surge capability of SCR. In this topology, three back-to-back SCR switches are connected in delta form and further engaged with the rotor circuit of DFIG through power dissipation resistors, working as the main circuit of crowbar, while the rotor side converter (RSC) is used to commutate the SCRs at the desired deactivation moment to disconnect the crowbar, allowing for resumption of the feedback control to DFIG. By this topology the harmonics introduced into the rotor circuit by the diode bride in the IGBT crowbar are got rid of and by this commutation method the overvoltage risk at turning off the IGBT is eliminated. With the simulative results on a 2 MW DFIG, the comparison with the IGBT crowbar is made. The feasibility of the proposed crowbar technique is further demonstrated with experiments on a laboratory-scale test rig.

Introduction

The ever growing installed capacity of wind turbines (WTs) has been increasing the penetration of wind energy into power system dramatically, posing unprecedented challenges to today's grid [1]. As a result, more and more stringent grid codes have been in place, especially for high power WTs. At present, it has been imperative to stay connected during a majority of grid faults, so as to minimize the negative impacts of large-scale wind energy integration on power grids [2,3].

Partially rated drive converter, combining with variable speed operation has made doubly fed induction generator (DFIG) widely equipped especially in high-power WTs [4,5]. Shown in Fig. 1 is a typical schematic of DFIG. The stator is connected directly to the power grid, while the rotor is interfaced through back-to-back voltage source converters (VSC) typically rated at 30% of the DFIG's nominal capacity. This topology strikes a good balance between the basic functionality of variable speed operation and independent control to active and reactive power, and cost-effectiveness. However, the direct connection of the stator circuits to the grid also makes it more vulnerable to voltage dips [3]. The sharp loss of exciting voltage due to voltage dips will force the stator flux trapped in the stator circuits, and consequently induce high transient back-EMFs in rotor circuits, posing a severe threat to integrity of the drive converter in terms of its limited capability. This has resulted in the complexity of low voltage ride through (LVRT) for the DFIG-based wind turbines.

To address this issue, many contributions have been made from different aspects. Although series grid-side converter operating as a dynamic voltage restorer [6–8], stator-side passive impendence methods [9,10], feedforward transient compensation [2,6], and demagnetization control strategies [11,12] illustrate the recent achievements in this field, crowbar technique is still a relatively mature solution at present and widely incorporated in today's commercial WTs to divert the outrush current and protect the converter [13–16].

With the requirements getting harsher, the conventional SCR-based passive crowbar solution is no longer acceptable, since it cannot be deactivated swiftly [17,18]. Active crowbar has become a dominant scheme for LVRT fulfillment, and is attracting a lot of attentions in academic community. In publications, researchers mainly focused on crowbar resistance design [19–22], or patterns to activate and deactivate the protection and to resume the feedback control quickly [13]. While an appropriate range for the resistance was defined in [19,20] in terms of the limits on fault current

* Corresponding author.
E-mail address: yangsy@hfut.edu.cn (S. Yang).

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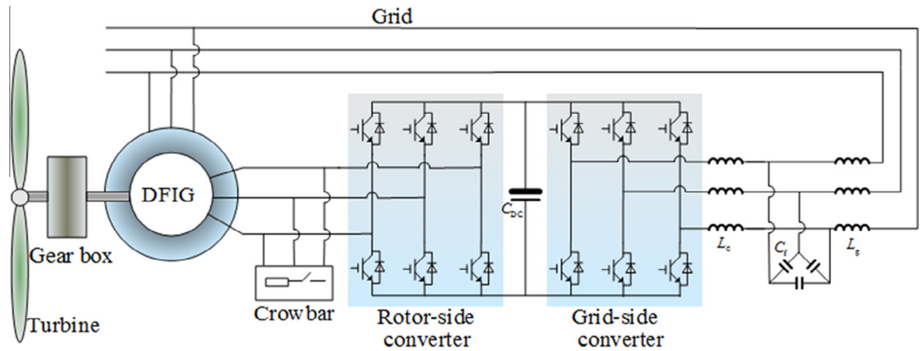

Fig. 1. Schematic of a typical DFIG system.

and consequent rotor voltage, an objective function referring to rotor current and DC-link voltage was defined in [21] attempting to further optimize choice within the allowable range. In [22], the crowbar resistance was determined by real-time simulation regarding the recognized extreme conditions with power and torque taken into account in addition to the limits. Meanwhile, the release procedure of crowbar by the fall of the rotor current magnitude below the preset threshold and the resumption of the converter control were elaborated in [13], intending to reduce the application periods to the maximum extent. Although these publications had advanced the crowbar technique, the designs of the crowbar resistance and associate analysis were mostly based on the simplified analytical solutions or real-time simulation. Accurately analytical analysis based research is still very rare in literature.

On the other hand, crowbar topology itself had not attracted due sufficient attentions, and almost all of these previous works were based on the well-known diode bridge configuration with integrated-gate bipolar transistor (IGBT) controlling the DC resistance (referred to as IGBT crowbar in following presentation), to minimize the number of the valuable switching devices, though a rectifier IGBT topology was mentioned as a comparison in [23]. Considering the magnitude of the current circulating through the IGBT, two single-phase DC crowbar topologies were proposed in [16] with the aim to reduce the overvoltage at turning off, lower the necessary capability of the costly IGBT devices and to make this popular crowbar topology adapted to higher power WTs, however, more IGBTs and diodes were demanded and the dimension was still very large.

Compared with IGBT, the surge capability of silicon-controlled rectifier (SCR) is much higher, which is beneficial for this specific application of crowbar in terms of the transient current spikes under voltage dips. Meanwhile, the high power oriented design of SCR itself allows it to be more cost-effective and reliable [24]. In addition, the property of higher switching frequency of IGBT, as a very important constituent of its cost, is redundant for this protection application. If SCR can be switched off artfully at the needed moment, it would be ideal in the constitution of active crowbar circuit. In this paper, three sets of back-to-back SCRs are configured in a delta form and engaged to the rotor circuits through power dissipation resistors, constituting the main circuit of the crowbar, while the rotor-side converter (RSC) is used to provide a reverse voltage for the SCRs in conduction to commutate and force them off at the moment of releasing the crowbar. Although the SCRs cannot be turned off by their gate drives, the crowbar circuit can be deactivated with the aid of the RSC almost in no time, and the swift resumption of the feedback control to DFIG is allowed. Therefore, the function of active crowbar is achieved with the RSC-aided SCR crowbar technique. Besides higher surge capability and cost-performance ratio benefited from SCRs, the harmonics in the rotor currents created by the diode bridge and the overvoltage risk at switching off the IGBT in the mostly used crowbar configuration are avoided in this newly designed SCR crowbar. All of these merits will render this topology favorable especially in future higher power WTs.

To demonstrate the performance of the SCR crowbar, comparison with the IGBT crowbar is made by simulation on a 2 MW DFIG for commercial WTs and the performance of the designed crowbar scheme is further demonstrated by experimental results on an 11 kW laboratory-scale test rig.

The main contribution of this paper is the design of a cost-effective and high reliable crowbar scheme, i.e. the SCR crowbar. The resistance and its effects on the transient characteristics are discussed based on a more accurate analytical analysis to the dynamic response of DFIG to voltage dips. The RSC-aided commutation and the action procedure are detailed. Following this section, the DFIG drive system, its behavior under voltage dip and the effects of crowbar resistance are discussed in Section ‘DFIG system’. The newly designed SCR crowbar topology and the associate control scheme are presented in Section ‘Crowbar scheme’. The performance of the proposed crowbar scheme is compared with the IGBT crowbar in Section ‘Comparison study with IGBT crowbar’, and in Section ‘Validation of the SCR crowbar scheme’ the scheme is comprehensively verified with simulative and experimental results.

DFIG system

DFIG model

Using the motor convention, the model of DFIG can be described with a set of equations in rotor reference frame, as

$$\begin{cases} \boldsymbol{u}_s^r = R_s\boldsymbol{i}_s^r + p\psi_s^r + j\omega\psi_s^r \\ \boldsymbol{u}_r^r = R_r\boldsymbol{i}_r^r + p\psi_r^r \\ \psi_s^r = L_s\boldsymbol{i}_s^r + L_m\boldsymbol{i}_r^r \\ \psi_r^r = L_r\boldsymbol{i}_r^r + L_m\boldsymbol{i}_s^r \end{cases} \tag{1}$$

where superscript “r” denotes the rotor frame reference; subscripts “s” and “r” denote stator and rotor variables; $\boldsymbol{u}$, ψ and $\boldsymbol{i}$ represent voltage, flux and current, respectively; R denotes resistance, L_s, L_r and L_m are the stator, rotor and magnetizing inductances, respectively; and $\boldsymbol{\omega}$ represents rotor-speed frequency excursing the synchronous frequency $\boldsymbol{\omega}_1$ by the slip one $\boldsymbol{\omega}_s$.

In the synchronous reference frame oriented to the stator voltage vector, the rotor voltage can be expressed with rotor currents, as

$$\begin{cases} u_{rq} = R_r i_{rq} + \sigma L_r p i_{rq} + \omega_{sl}\left(L_m^2 i_{ms}/L_s + \sigma L_r i_{rd}\right) \\ u_{rd} = R_r i_{rd} + \sigma L_r p i_{rd} - \omega_{sl}\sigma L_r i_{rq} \end{cases} \tag{2}$$