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Appropriate crowbar protection for improvement of brushless DFIG LVRT during asymmetrical voltage dips

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This paper proposes effective approach for determining appropriate crowbar resistance value to be able to improve the brushless doubly fed induction generator ride through capability during any asymmetrical voltage dip scenarios. The brushless DFIG has great potential for wind power plants particularly in offshore applications where maintenance is a major concern. Dynamic behavior of the machine is studied using two axis model and a more precise equivalent circuit model is extracted for analyzing machine behavior under fault conditions.

Important limits and constraints in the use of crowbar are identified and discussed in detail. It is shown that large crowbar values can lead to considerable overvoltage which can damage the power electronics converter. Hence, crowbar voltage is an important consideration in crowbar implementation. Efficiency of the crowbar providing ride through capability is investigated for asymmetrical faults by using MATLAB/Simulink for a D180 brushless DFIG prototype.

1. Introduction

Renewable energy technologies promise the abundant energy gathered from self-renewing resources such as the sun, wind and plants. They are seen as a reliable alternative to the traditional energy sources such as oil, natural gas, or coal [1]. Among these, wind energy guarantees low pollution and operational costs. About 70% of the installed wind turbines are doubly-fed induction generators (DFIG) [2] due to use of a fractionally rated power electronic converter as well as being variable-speed, reducing overall cost of the system.

By increasing wind power penetration in power systems, grid code requirements, such as low voltage ride-through (LVRT) capability has attracted more attention for wind farms. Based on such requirements, wind turbine generators must remain connected to the grid and actively contribute to the system's stability during various grid fault disturbances. Reliability of some generators used in onshore applications, is not adequate for offshore applications. Hence, system design can be changed by reducing the wind turbine components [3]. Absence of slip rings and brushes in the brushless DFIG (BDFIG) with low weigh two stage gearbox is an advantage for offshore application where maintenance is vital and expensive. This necessitates an in depth study of the machine dynamic behavior and its LVRT capability in fulfilling the grid code requirements.

In view of reduced complexity and robustness of the proposed schemes for DFIG LVRT, hardware based solutions are favored [4]. Design and implementation of a series voltage sag compensator during grid disturbances are presented in [5]. To support reactive power injection during grid faults, application of flexible AC transmission systems (FACTS) such as STATCOM [6] and gate-controlled series capacitor (GCSC) [7] are proposed in literature. Such methods effectively enhance control scheme of generators during the grid faults. However, their application increases complexity and overall cost of the system [8]. Another concern in LVRT problem is transient power oscillations which can be addressed through implementing energy storage systems (ESS) [8,9]. Although they can provide acceptable transient performance [10], they need more space for installation, which is an important concern in practice, especially in offshore application. In comparison with aforementioned approaches, the crowbar protection method is relatively simple and economic, making it a feasible choice for LVRT problem in practice. The use of crowbar resistor for symmetrical voltage dips is proposed for DFIG in [11]. An activation scheme based on neural network analysis is proposed in [12] and appropriate activation time for crowbar circuit is determined in [13]. Single phase crowbars are proposed and compared to commonly-used three phase crowbar in [14] for a large scale

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Nomenclature

Vectors and symbols
I, V, λ current, voltage, flux linkage
R, L resistance, self inductance
t, f, ω time, frequency, angular speed
PW, *CW* power winding, control winding
p, N number of pole pairs, number of nests
M_{1r}, M_{2r} mutual inductance of PW and rotor, mutual inductance of CW and rotor
R'_2, L'_2 CW transient resistance, CW transient inductance
σ damping coefficient of PW flux
Ph-G phase to ground voltage dip
Ph-Ph-G phase to phase to ground voltage dip
Ph-Ph phase to phase voltage dip
$R(Ph\text{-}G)$ appropriate crowbar value for phase to ground voltage dips
$R(Ph\text{-}Ph\text{-}G)$ appropriate crowbar value for two phase to ground voltage dips
$R(Ph\text{-}Ph)$ appropriate crowbar value for phase to phase voltage dips

Superscripts
1, 2 PW, CW reference frame
$*$ conjugation operator

Subscripts
1, 2, r PW, CW, rotor
p, n, z positive, negative and zero sequence
Pre, f refer to pre-fault values of variables and during fault values of variables

DFIG-based wind turbines. However, due to their topology they may reduce reliability of the system. In such studies, the resistance value are selected among a few alternatives and their performance are checked to fulfill LVRT requirements [15], but important limits and constraints in the use of crowbar are not identified and discussed in detail. Moreover, to date no hardware based approaches have been proposed for BDFIG LVRT during asymmetrical faults. In this paper, with considering a more detailed dynamic equivalent circuit of machine, the values of resistors are calculated analytically to meet all the constraints. This methodology leads to a simple and optimum resistance value for crowbar circuit to guarantee acceptable LVRT for every voltage dip scenario.

Another control scheme to reduce DFIG rotor currents and oscillations during and after voltage dips, using a crowbar, is proposed in [16]. Furthermore, considerable interest has been given to control and design of the BDFIG. Parameter estimation models, including the coupled circuit model and steady state equivalent circuit parameters are verified by experiments in [17,18]. In [19], it is shown that dynamic behavior of the brushless DFIG during voltage dips is similar to that of a DFIG during symmetrical voltage dips. Hence, DFIG LVRT solutions can be similarly applied to a BDFIG with modifications. A control method is proposed to enable successful ride through of the BDFIG during symmetrical voltage dips in [20]. By performing a converter rating optimization, another control strategy is presented in [21], and an acceptable LVRT performance is reported without the need for additional hardware. However, such methods make the control systems particularly complicated when control coordination between normal and fault operation is needed [22]. Therefore, the use of a crowbar and series dynamic resistors (SDRs) is presented to improve BDFIG symmetrical LVRT in [23]. The research suggests a higher leakage inductance making it more difficult to control the PW reactive power by the machine side converter (MSC), but limiting the MSC current amplitudes during LVRT.

It is apparent that improved design will provide lower resistances and leakage inductances to achieve increased efficiency. Therefore, this trade-off assessment during the generator design process is important [24]. Considering novel modeling and design methodologies for the BDFIG [25,26], safe operation for every BDFIG size cannot be guaranteed during voltage dips and this necessitates further investigation of hardware based LVRT solutions.

To date the effects of machine parameters on LVRT capability has not been investigated and an accurate analytical study is required. This paper initially models LVRT behavior of the BDFIG. Dynamic behavior of the machine under fault conditions is examined and the effects of various faults and machine parameters are investigated analytically. The aim of this paper is to assess the use of crowbar resistor for successful ride-through of BDFIG during severe voltage dips. In addition, the paper presents analytical calculations for choosing an appropriate crowbar resistor value for the BDFIG during asymmetrical voltage dips. The result of this study ensures practical LVRT capability of the BDFIG.

2. BDFIG dynamic model

The BDFIG is formed of two cascaded induction machines. Its rotor windings are short-circuited to achieve a rigid structure without the need for slip rings and brushes. The nested loop type rotor consists of several nests, each representing a single rotor circuit containing several loops. It is designed specially to achieve indirect cross coupling between two stator windings. The number of rotor nests should be equal to the summation of stator winding pole pairs [27]. These two stator windings known as power winding (PW) and control winding (CW), have different pole number to avoid direct magnetic coupling [28]. The PW is connected to the grid and the major portion of power is transferred to the grid through this winding. The PW generates a rotating magnetomotive force (MMF) in the air gap at grid frequency. The CW is connected to the grid through the fractionally rated bidirectional converter that consists of two back to back converters. The machine side converter (MSC), controls the CW current and voltage excitation. Due to the existence of cross-coupling between the CW and PW, the CW current affects the PW current. The grid side converter (GSC) controls the dc-link voltage.

The authors have investigated various operating modes of the BDFIG in [29]. The most favored mode of operation is synchronous mode in which the production of two fields by the PW and CW rotating at the same electrical speed with respect to the rotor is necessary [30]. Furthermore, due to the chosen number of rotor nests, direction of rotation of the PW MMF with respect to the rotor should be opposite to that of the CW MMF to achieve cross-coupling. The synchronous speed is determined by:

$$\omega_1 - p_1\omega_r = -(\omega_2 - p_2\omega_r) \quad (1)$$

And if the CW current is fed with dc, the natural speed is found from [17]:

$$\omega_n = \omega_1/(p_1 + p_2) \quad (2)$$