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Wind farm node connected DFIG/back-to-back converter coupling transient model for grid integration studies

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ABSTRACT

This paper presents the explicit electromagnetic transient model of a Doubly Fed Induction Generator (DFIG), that includes its coupling with the back-to-back converter, when the generator/converter set is connected to the wind farm's Thevenin equivalent, as seen from DFIG's terminals. Besides that, DFIG's grid side converter control system is defined in detail, so that expressions for the direct tuning of all compensators are provided. The overall electromechanical wind generator model includes 24 state variables: four mechanical, eleven electrical, and nine more – one for each controller – associated to the control system. The developed model is complemented with a state machine that implements the sequential control among the different stages that define its operational modes. Simulation and experimental results show that the developed model is able to predict the behaviour of the generator in short and long term scenarios.

1. Introduction

The increasing penetration of wind power augments in parallel the importance of ensuring that it does not adversely affect the power quality, security, and reliability of each power system network, during both steady-state operation and under contingencies. In this scenario, Grid Operators develop specific grid codes for wind power plants in order to ensure the safe, reliable and economic operation of the power system [1–4]. Thanks to the developments that have been carried out in power electronics, current variable-speed wind turbines are able to meet the requirements defined by the grid codes [5–9].

In this context, traditional representations of wind farms must be updated to properly model their interaction with the grid and correctly predict security and/or reliability issues. The aggregated approach represents a wind farm by one equivalent wind turbine with re-scaled power capacity [10–17]. However, and as it has been shown in other works, a multi-machine model not only describes more precisely the behaviour of the wind farm, but it is also indispensable for the design and validation of new operational strategies [18–22].

In [23] a simplified model of a DFIG wind turbine to be implemented by commercial software vendors is defined by EPRI, based on discussions of WECC Renewable Energy Modeling Task Force (REMTF) and International Electrotechnical Commission Technical Committee 88, Working Group 27 (IEC TC88 WG27) meetings. The flux dynamics of the generator are eliminated, and the active and reactive currents injected to the grid are represented by controlled current sources and first order transfer functions.

Other works use a more detailed model of the DFIG generator to obtain a better accuracy, considering the electrical transients of the stator and/or rotor. In some cases, stator variables are represented as algebraic ones in order to reduce the complexity of the model [11,14–16]. However, taking the stator electrical dynamics into account becomes necessary if the transient evolution of the currents is to be analysed [12,13,17,22,24–26], for example in the analysis of fault conditions.

Power converters are typically considered ideal and the DC bus voltage dynamics is modelled as a power flow equation [22,27,28]. Furthermore, even if in many works the model of the filter of the grid-side converter (typically of L, LC or LCL type [29,30]) is neglected [10,11,15,16,28], it is necessary to take it into account in order to properly represent the existing coupling between the stator and the rotor of the DFIG generator.

The objective of this paper is the development of an equivalent model of a DFIG connected to the internal network of a wind farm

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for transient response analysis, with a proper trade-off between accuracy and computational burden, that can be used to simulate a complete multi-machine wind farm. The back-to-back converter is assumed to be ideal and an LCL grid filter is used due to its capacity to better attenuate harmonics in comparison to L filters.

The paper is structured as follows: the main components of the defined model are listed in Section 2. A unified model of the DFIG generator, LCL filter and the step-up transformer that connects the generator to the wind farm node is presented in Section 3. Section 4 explains the control of the grid-side converter, formed by three nested loops. Then, Section 5 summarises all the developed transient model, and also proposes a state-machine to implement the sequential control among the different stages that define the operational modes of the wind generator. The behaviour of the proposed model is analysed in different working conditions, and simulation and experimental results are shown in Section 6. Finally, the conclusions obtained from this research work are explained in Section 7.

2. Components considered in the system

Fig. 1 shows the layout of the grid-connected DFIG, whose model must combine the major fidelity with the suitability for the development of multi-machine wind farm models. To achieve this goal, it includes the following elements:

- An LCL filter/DFIG coupling equivalent model, that eliminates the algebraic loop arising from their connection to the step-up transformer. According to the Spanish regulation, a Dyn step-up transformer has been considered, which connects the DFIG with the internal network of the wind farm.
- Back-to-back converter (B2B), described as a set of two controlled voltage sources coupled through a DC-link. The rotor-side converter (RSC) is directly connected to the machine's rotor, while the grid-side converter (GSC) is connected through an LCL filter to the low-voltage winding of the transformer. Given the switching frequency of power converters – in the range of kHz – a model of their switching behaviour is considered too detailed when developing a DFIG model that is oriented to the development of multi-machine wind farm models, because integration steps should be in the range of µs, and this would unnecessarily slow down the simulations.
- LCL grid filter, given that they show better performance, minor volume and cost, as well as higher power densities than L filters; although their dynamics are very influenced by two resonant frequencies, which may give rise to stability issues [8].

3. LCL filter/DFIG coupling equivalent model

The equivalent model of the coupling between the LCL filter and the DFIG is derived from the circuit shown in Fig. 2. The main issue of this layout is that GSC's LCL filter is connected to the DFIG's stator voltage. In most cases, the bibliography assumes that the DFIG is connected to an infinite Busbar and, as a consequence, there is no real coupling between stator and rotor sides of the generator [22].

However, the only presence of the step-up transformer that connects the generator to the wind farm's medium voltage network overrules this assumption. And this coupling is even tighter as the Thevenin impedance at the wind farm node increases, like in the case of weak electrical networks. Therefore, it is mandatory to develop an integrated model that takes into account the intrinsic coupling between the LCL filter and the DFIG.

The electromagnetic transient model of the DFIG, expressed in "D–Q–d–q" axes [25], considers the value of the stator voltage V_s as an input whose value must be previously known, in order to obtain its dynamic evolution. But, the equivalent model of the transformer includes a series inductance L_t that introduces an algebraic loop in the model. In the state-space, DFIG currents are expressed as a function of V_s, i.e. $di_s/dt = f(V_s)$ and, at the same time, due to L_t, V_s is a function of di_s/dt.

Therefore, a unified representation of this coupling, where di_s/dt is actually a function of known variables, such as $di_s/dt = f(V_D, V_F, L_t, L_{Fg})$, needs to be developed. As a first step, once choosing i_s and i_{Fg} as independent state variables, transformer's low voltage can be expressed considering DFIG's stator voltage or, alternatively, LCL filter's capacitor voltage,

$$\begin{aligned} V_y = \frac{1}{\sqrt{3}}\mathbf{M_V}V_D &= L_t\left(\frac{di_s}{dt} + \frac{di_{Fg}}{dt}\right) + V_s \\ &= L_t\left(\frac{di_s}{dt} + \frac{di_{Fg}}{dt}\right) + L_{Fg}\frac{di_{Fg}}{dt} + V_F \end{aligned} \tag{1}$$

where V_F denotes the LCL filter's capacitor voltage, $\mathbf{M_V}$ represents the voltage ideal transformation matrix of the Dyn step-up transformer [18], and V_D and V_y are, respectively, voltages at the high side – Delta – and low side – wye – of the ideal part of the transformer.

Besides that, the electromagnetic transient DFIG model in "D–Q–d–q" axes can be expressed as follows,

$$\frac{di_s}{dt} = A_s V_s + B_s \tag{2}$$

$$\frac{di_r}{dt} = A_r V_s + B_r \tag{3}$$

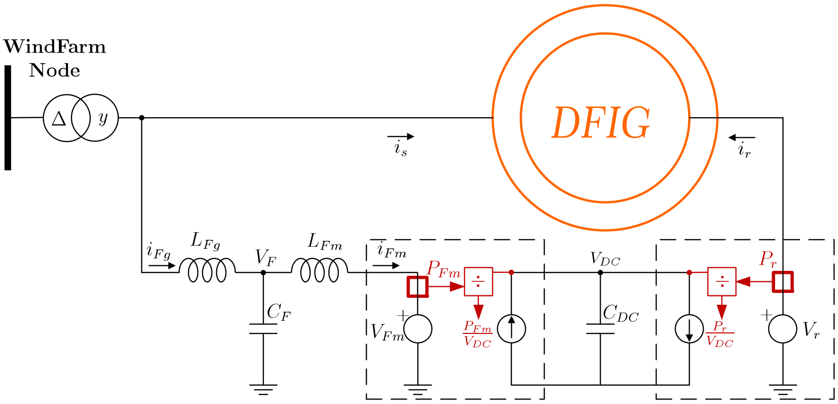

Fig. 1. Grid-connected DFIG layout, including the rotor side back-to-back converter.