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Complete wind farm electromagnetic transient modelling for grid integration studies

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ABSTRACT

This paper presents a modelling methodology to analyse the impact of wind farms in surrounding networks. Based on the transient modelling of the asynchronous generator, the multi-machine model of a wind farm composed of *N* generators is developed. The model incorporates step-up power transformers, distribution lines and surrounding loads up to their connection to the power network.

This model allows the simulation of symmetric and asymmetric short-circuits located in the distribution network and the analysis of transient stability of wind farms. It can be also used to study the islanding operation of wind farms.

1. Introduction

Distributed energy generation is becoming a larger part of the total generation of power systems worldwide and, in particular, wind energy represents 50% of the total renewable energy in Europe. Aggregate wind power installed in the European Union (EU-27) at the end of 2007 was 56,535 MW, that covers 3.78% of EU-27 electricity consumption [1]. In Spain installed wind power was 15,145 MW, being the second country in the world.

Wind generation provides several advantages over other power generation systems, such as no cooling water use, no carbon dioxide emissions, proximity of generation to local loads and unloading of transmission lines. It may be asserted, however, that as installed wind power expands, issues related to integration, stability effects and voltage impacts become increasingly important [2].

Due to this fact, several transmission system operators have defined specifications for connecting wind farms to their networks [3–5]. The purpose of the specifications is to ensure the essential properties for power system operation as regards security of supply, reliability and power quality. These specifications include frequency and voltage quality conditions, active and reactive power control ability, stability and protection requirements in the case of faults in the power system, and fault ride through capability.

Regarding transient stability, Eltra specification requires that the interaction between the power system and the wind farm at faults in the power system must be verified by means of simulations, and it is the responsibility of the plant owner to provide the necessary models for these simulations [3].

In this context, it is necessary to develop accurate models of wind farms in order to evaluate their impact and predict the farm's influence on the dynamic behaviour of the electrical system [6–11]. With these dynamical models it could be possible to create difficult to test scenarios, such as balanced and unbalanced short-circuits and loss of mains [12–14]. Furthermore, these models could support the design of new protection systems [15], new control algorithms [16–18] and operational strategies to improve their real time exploitation [19], enhancing their collaboration to the support of the electrical grid.

Given that a mathematical modelling of wind farms is a must for their grid integration, a first question arises immediately: which is the appropriate model to analyse consistently the impact of wind farms to the surrounding electrical network?

Typically, two main wind farm modelling tendencies have been observed in references: the aggregated model and the detailed or multi-machine model. The aggregated approach represents a wind farm by one equivalent machine with re-scaled power capacity [6,7]. This model has been applied to the study of voltage stability of the power system [8] as well as to transient stability [9,11], and it has also been tested for load flow analysis [10,20]. On the other

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hand, it allows, under certain conditions, the analysis of transient stability of large wind farms [12,13,21] and their control [16].

The drawback of aggregated models is that they do not reflect effects due to the real operation point of each wind generator, such as mutual interactions or power oscillations between wind turbines. But it is often claimed that aggregated models are able to reflect worst-case scenarios when electrical disturbances affect the normal operation of the wind farm [22]. However, this has resulted not to be exact because they do not describe the general behaviour of wind farms, except in very particular operating conditions [13,19]. To solve this problem several authors have proposed an intermediate detail level where large wind farms are modelled based on wind turbine groups, e.g., an equivalent wind farm for each turbine row [12].

With regard to detailed models, due to their inherent complexity, it is more difficult to find contributions in the bibliography. Several references suggest that multi-machine models are inappropriate because their simulations are much more demanding computationally and that, essentially, the potential advantages do not pay off the additional modelling effort.

But, despite this stance, just a few authors have developed solutions to the detailed model of large wind farms, from two main ways to set out the problem. The first one is the automatic development of simulation models by means of simulation programs, such as PSCAD/EMTDC or SimPowerSystems, which numerically compute the state-space model of the system. With this approach short term voltage stability of the wind farm when the external network is subjected to short-circuits [14], or when there are wind speed changes [23] is analysed. The second option is to explicitly obtain the overall network model, as for the simulation—assuming a simplified generator model—and short-circuit study in an isolated system [24,25]. Obviously, this second approach provides improved knowledge about the system, and interactions among generators are studied with more detail.

This paper presents a methodology to develop electromagnetic transient simulation models of wind farms, to predict their behaviour under normal operating conditions and also under electrical disturbances. It will be assumed that the wind farm will have a radial shape, that is, several generators connected to a common bus bar and, from this a connection line as far as the Point of common coupling to the electric power system.

Simulation models will be developed from a double point of view. Firstly, development of detailed multi-machine models, where each generator has its own point of operation. And secondly, simplified aggregated or macro-generator modelling. Several simulation results of a spanish wind farm, obtained after the implementation of the models in Simulink, are also presented.

2. Electromagnetic transient modelling of the wind generator

In the general case, the electromagnetic transient model of the generator has six differential non-linear equations called *the general three phase model of the machine*. This model describes the evolution of rotor and stator voltages and currents [26]. But, in this model, all six equations are interdependent due to leakage inductances.

To deal with this problem several transformations have been proposed—Clarke's transformation, Park's transformation—that express the original differential equations in different frames of reference, as shown in Fig. 1, where the cross-section of an induction generator containing stator and rotor windings, is depicted. Using these transformations it is possible to refer stator and rotor variables either in the stationary frame "$D-Q-0$", or in a reference frame that rotates with the rotor at its electrical speed ω_r, "$\alpha-\beta-0$" [27].

When induction generator variables are referred to their natural frames, the stator side is referred to the stationary frame

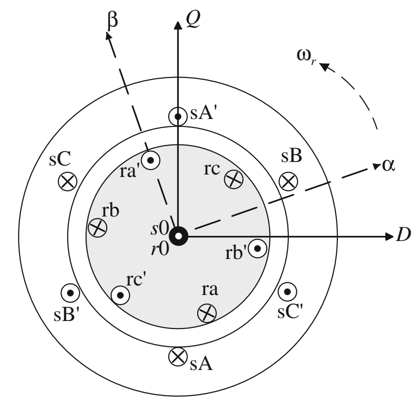

Fig. 1. Schematic cross-section of induction generator.

"$D-Q-0$" and the rotor side is referred to the rotating frame "$\alpha-\beta-0$". This "$sD-sQ-s0-r\alpha-r\beta-r0$" model is also called *"Quadrature-Phase Slip-Ring"* [26].

As Fig. 1 shows, direct and quadrature axes of both frames of reference: stationary—D, Q—and rotating—α, β—are confined in the cross-section of the machine, while zero sequence axis —0—is aligned with the rotor shaft. As a result, zero sequence components are decoupled from direct and quadrature ones, so the original model of six interdependent differential equations leads to a more accessible modelling with just four coupled differential equations plus two independent differential equations.

Furthermore, as zero sequence components cancel out in the case of balanced systems, it is usual to apply only "$D-Q-d-q$" or "$D-Q-\alpha-\beta$" models [16]. Owing to this fact, Clarke's transformation is usually called three to two-axes transformation. However, for a general research about the behaviour of generators under all kind of disturbances (symmetric and asymmetric), this assumption leads to erroneous results, since, in such cases, zero sequence components take non zero values.

In this paper, stator and rotor variables will be expressed in the stationary reference frame "$D-Q-0$", because this modelling approach has three main advantages: firstly electrical parameters of the induction machine are easily calculated from steady-state circuit parameters. Secondly, state equations are much simpler than those of *"Quadrature-Phase Slip-Ring"* model. And finally, calculation of the electromagnetic torque of the generator is straightforward, as we will show below. This model is also known as *"Quadrature-Phase Commutator"* [26].

Keeping in mind all this considerations, the electric model might be expressed through (1)–(6) with currents i_{sD}, i_{sQ}, i_{s0}—for the stator side—i_{rd}, i_{rq}, i_{r0}—for the rotor side—, as electrical state-variables of the electromagnetic transient model. This model will be referred as "$D-Q-0-d-q-0$" [19].

$$\frac{\mathrm{d}i_{sD}}{\mathrm{d}t} = \frac{L_r(v_{sD} - R_s i_{sD}) + L_m[\omega_r(L_m i_{sQ} + L_r i_{rq}) + R_r i_{rd} - v_{rd}]}{L_m^2 - L_s L_r} \tag{1}$$

$$\frac{\mathrm{d}i_{sQ}}{\mathrm{d}t} = \frac{L_r(v_{sQ} - R_s i_{sQ}) - L_m[\omega_r(L_m i_{sD} + L_r i_{rd}) + R_r i_{rq} + v_{rq}]}{L_m^2 - L_s L_r} \tag{2}$$

$$\frac{\mathrm{d}i_{s0}}{\mathrm{d}t} = \frac{-R_s i_{s0} + v_{s0}}{L_{ls}} \tag{3}$$

$$\frac{\mathrm{d}i_{rd}}{\mathrm{d}t} = \frac{L_m(R_s i_{sD} - v_{sD}) - L_s[\omega_r(L_m i_{sQ} + L_r i_{rq}) + R_r i_{rd} - v_{rd}]}{L_m^2 - L_s L_r} \tag{4}$$

$$\frac{\mathrm{d}i_{rq}}{\mathrm{d}t} = \frac{L_m(R_s i_{sQ} - v_{sQ}) + L_s[\omega_r(L_m i_{sD} + L_r i_{rd}) + R_r i_{rq} + v_{rq}]}{L_m^2 - L_s L_r} \tag{5}$$

$$\frac{\mathrm{d}i_{r0}}{\mathrm{d}t} = \frac{-R_r i_{r0} + v_{r0}}{L_{lr}} \tag{6}$$