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Review

Aggregated models of permanent magnet synchronous generators wind farms

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ABSTRACT

This paper evaluates the responses of three aggregated models of a wind farm consisting of variable speed permanent magnet synchronous generator wind turbines when wind fluctuations or grid disturbances occur. These responses are compared with those of the detailed wind farm model, in order to verify the effectiveness of the studied aggregation methods for this type of wind farms. The equivalent wind farm models have been developed by adapting different aggregation criteria that already exist in technical literature and had been applied to other technologies. In this work, these methods have been modified to suit them to the permanent magnet synchronous generator technology. The results show that the three aggregated models provide very similar results to the detailed model, both in the evolution of active power when fluctuations in wind speed occur, and in the active power and DC-link voltage during the two simulated voltage dips. Notably, the aggregated model with an approximate mechanical torque offers excellent results.

1. Introduction

Interest in wind energy continues experiencing a progressive growth worldwide due to lower generating costs, an increase in electricity demand and a rising concern for the environment. In fact, the worldwide wind capacity reached close to 300 GW by the end of June 2013 and all wind turbines globally installed by mid-2013 can generate around 3.5% of the world's electricity demand [1]. In particular, according to last data published by *Red Eléctrica de España (REE)*, in 2013 wind energy has been the technology that has contributed more to cover the annual electricity demand in Spain for the first time, with a 21.3%, being located a little above the nuclear which has achieved a 21% contribution [2]. Consequently, nowadays wind energy is a real alternative to conventional energy what allows diversification of energy sources and reduces the dependence on imports.

Penetration of wind energy in the power system is huge so that, the performance of the power system depends on the behaviour of its main characters. This performance is supervised by the system operator, who needs to know beforehand the behaviour of all constituents, in particular, all the generation units, like wind farms. On the order hand, in order to get the maximum of renewable resources, it is a common practice not to restrict wind generation.

Hence, it is for these reasons that there is a need for developing wind farm (WF) models that represent the collective reaction of wind turbines (WTs) to grid disturbances and different wind conditions. But this task is computationally very demanding due to the size of WFs, which keeps increasing. Therefore, when the entire WF is simulated by representing each individual turbine, the response simulation time is very slow because of the complexity of the system of equations that describes it. Then, to study the behaviour of one or more WFs within the power system in transient stability studies, it is common to represent the whole WF by groups of turbines or by one single equivalent turbine, what is known as an *equivalent or aggregate model* of the WF. Thereby, the complexity of the system and the calculation time are reduced without losing information on the WTs collective response.

Equivalent models by adding variable speed WTs are only being studied since a few years ago and most of the investigations are focused on WFs with doubly fed induction generators (DFIG) WTs [3], [4]. However, this configuration is being gradually replaced by

Abbreviations: WF, wind farm; WT, wind turbine; DFIG, doubly fed induction generator; PMSG, permanent magnet synchronous generator; EWT, equivalent wind turbine; SCIG, squirrel cage induction generator; AWF, aggregate wind farm.

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the permanent magnet synchronous generator (PMSG) WT, which is becoming the most used configuration by most manufacturers, due its attractive characteristics versus other configurations [5]. Therefore, there is a need to carry out aggregated models by adding variable speed PMSG WTs and, nevertheless, there is evidence in the literature that such models of WFs have hardly been developed.

After analyzing the state of the art of aggregate models of WFs with variable speed wind turbines, it can be pointed out that to represent a variable speed WF behaviour in the presence of wind fluctuations or grid disturbances, basically, there are two aggregation methods. However, each author adapts these aggregation methods to his targets and changes the level of reduction depending on the type of the study to be performed, the wind distribution within the WF and the level of accuracy required.

The first main aggregation method is the simplest and most used one and it is based on the aggregation of a whole WF into a single equivalent WT. The mechanical and electrical parameters of the equivalent wind turbine (EWT) are scaled properly and its rated power is the sum of the nominal power of each WT within the WF [3,6,7]. In this aggregation method it is assumed that all WTs within the WF are receiving the same wind and, therefore, all the machines are producing the same electrical power. However, although the order of the WF model can be highly reduced and, in consequence, the simulation time, the WF generating capacity is overestimated when this aggregation method is used, since the variation of wind speed within the WF due to its layout has not been taken into account and, therefore, the result is not accurate enough. So a single equivalent machine with a uniform wind speed distribution is not a good solution to represent the behaviour of a whole WF [8].

This problem can be solved with a variation in the described aggregation method: grouping together the WTs with similar incoming wind speeds within a WF and replacing them by an EWT. Then, the aggregate WF model will have so many EWTs as groups of machines with identical wind conditions [3,9]. The results of this method are more accurate but, as there are many WFs with different wind speed conditions within it, the resulting equivalent model may need many EWTs to represent the WF, which can result in long simulation time [8].

In Refs. [4,10] are presented variations of the one-machine aggregate model. In Ref. [10] the EWT receives an equivalent incoming wind, which is derived from the power curve and the wind experienced by each WT, being identical all of them. Although this method allows a reduction of the equivalent model order, its main disadvantage is that different WTs can not be aggregated because the equivalent system power curve can not be estimated. In Ref. [4], the proposed aggregation method results in an EWT where the mechanical systems of WTs are also aggregated. This method allows a whole WF to be represented at PCC to grid even when different wind turbines are operating with different incoming winds.

The second main aggregation method to represent a variable speed wind farm behaviour in the presence of wind fluctuations or grid disturbances is based on aggregating just the electrical system and modelling the mechanical system of each individual WT in order to consider the different wind speed conditions within the WF and even different technologies [11,12].

In Ref. [12] a dynamic simplified model of each individual WT is used to approximate their operation points according to the incoming wind. Then, the generator mechanical torque of the individual WTs are aggregated and the resulting torque is applied to the equivalent generator system. The results obtained with this aggregation method are more accurate than the ones obtained from the single equivalent machine or its variations, but some authors consider that the number of differential equations required to model the dynamic simplified WT is still reasonably large [8].

These aggregation methods can be summed up as shown in Table 1.

As aforementioned, despite the boom experienced by the PMSG WTs in the last few years, aggregated models of WFs with PMSG WTs barely exist in technical literature. For this reason, in this paper three aggregation methods from the summarised in Table 1 have been used to develop three equivalent models of WFs with variable speed PMSG WTs to study dynamic power systems. The most extended methods are analysed in this work:

- Method 1-Variation 2, which is named in this work *equivalent wind method*, is first proposed in Ref. [10] for squirrel cage induction generator (SCIG) and DFIG WTs.
- Method 1-Variation 3, which is named in this work *equivalent wind turbine rotor method*, is first proposed in Ref. [4] for variable speed DFIG WTs.
- Method 2, which is named in this work *approximate mechanical torque method*.

The procedure used to validate the developed equivalent models against the detailed WF model is based on the method proposed by the Working Group 21 of the IEA Wind [13] for variable speed DFIG WFs, adapting some of these requirements to the WTs that are studied in this work, to the best of the author knowledge.

The paper is organized as follows: Section 2 describes the detailed adopted model of the PMSG WT and its control system; Section 3 explains the aggregation methods used, Section 4 evaluates and discusses the responses of the equivalent models of the studied WF when wind fluctuations or grid disturbances occur and, finally, Section 5 presents the conclusions extracted from this research.

The software used for simulations is MATLAB/Simulink.

2. Detailed adopted model of a wind turbine

2.1. Wind turbine configuration

A typical configuration of a PMSG WT is shown in Fig. 1 and the equations that define the models of the different WTs components are given in Appendix A. These equations have already been described in Refs. [14,15], according to widely used PMSG WT models in the literature [16,17].

2.2. Wind turbine control system

The wind turbine consists of two coordinate control systems: the frequency converter control system and the blade pitch angle one. The WT control system used in this paper is already described in Ref. [15].

Depending on the objectives sought by each author, different control strategies are used in the generator-side converter control systems: Rotor speed control strategy (getting the reference of the generator-side converter from the measured wind speed [18–20] or from the measured electrical power [21]), electrical torque control strategy [22,23] and power control strategy [17,18,24,25]. In this work, the power control strategy has been adopted because in presence of a wind fluctuation this control strategy provides a smoother behaviour, although the WT system takes longer to restore the steady-state. Hence the WTs components are less stressed and the risk of structural damages to the WT components is lower [15,26]. Fig. 2 shows the schemes of the generator-side and the grid-side converter control systems.

On the other hand, regarding the pitch angle control system, as power control is the strategy applied to the outer loop of the generator-side converter control system and since it is a speed

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