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Modeling dynamics and control of type-3 DFIG wind turbines: Stability, Q Droop function, control limits and extreme scenarios simulation

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ABSTRACT

In this paper, a type-3 DFIG wind turbine is considered for a time domain dynamical study and mathematical modeling. The paper provides a full differential equations based model that is implementable by stiff solvers, such as Matlab ODE15s. The proposed model is validated vs. real measured data. The paper focuses and investigates further the so-called Q Droop function integrated with the wind turbine control system. Even with promising experimental results presented by General Electric studies, this function has rarely been studied throughout the literature. The paper emphasizes the effect of adding the Q Droop function to the reactive power control, and how this affects the whole dynamics in the system. We provide stability and control limits analysis for the system with and without the Q Droop function. Our results supported by simulations suggest the importance of the Q Droop function for stabilizing the system during sudden changes in wind speed, terminal voltage, or a severe drop in impedance. The paper also shows that the system has attraction limits that exceed the control limits suggested by General Electric and others. This can lead to either relaxing/changing the limiters or re-evaluate the state of the art modeling literature.

1. Introduction

The generation of renewable energies is increasing rapidly when compared to fossil fuels. According to [1], wind is the fastest growing renewable energy source. In the last two decades, modeling the control components of Wind Turbine Generators (WTGs) and their dynamics has been a rapidly growing area of research. As found in [2], type-3 WTGs are more efficient in extracting power than other types. The review [3] has a detailed study of the Coefficients of Performance (C_p) for type-3 and showed that C_p can go up to a 0.4-0.5 efficiency of extraction. Most of the studies in the literature, such as, General Electric's (GE) studies [4,5] and Electric Power Institute's study [6], suggested Doubly Fed Asynchronous/Induction Generator (DFAG/DFIG) technology for WTGs. Therefore, we consider the type-3 DFAG/DFIG in our paper.

In the literature, there are many sources and studies, mostly in transfer functions (frequency) domain for type-3 WTGs DFIG-based models. Studies such as, but not limited to [4,7,8] explain the modeling aspect in greater detail, while studies such as, but not limited to [9–12] provide partial modeling focused on some parts of the WTG dynamics. The paper [13] studied small-signal stability, showed that as the impedance drops the system loses stability, and performed eigenvalue analysis, all in transfer function domain. Fewer studies analyzed the model in time domain. However, having the model in time domain is necessary for stronger nonlinear studies. The papers [14–17] introduced some differential equations models while performing their analysis. Both [14,15] performed parameter sensitivity analysis, while [16] studied stability and bifurcation. Also, Miller et al. [18] summarized some of the important results the GE team presented in [4,5]. The topic of [17] is what we are extending in this paper. We are extending the modeling part, simulation results, and adding an entire section of data validation.

Motivation and objectives of this paper:

1) Modeling efforts in time domain for the WTG system, as discussed in the introduction by detail, are scarce. In our previous publications [15–17,19,20] the WTG model was only partially introduced, however, not generalized to include the complex/entire scale of all controls included in major academic resources, such as [13], or manufacturer reports, such as [4,5]. Also, our recent mathematical paper [21], meant to explore the pure mathematical properties (convergence and uniqueness of solutions) for a possible differential equations model to WTGs, laying the ground for a possible comprehensive modeling work that benefit the power systems and/or wind control communities. In this regard, the reader may refer the

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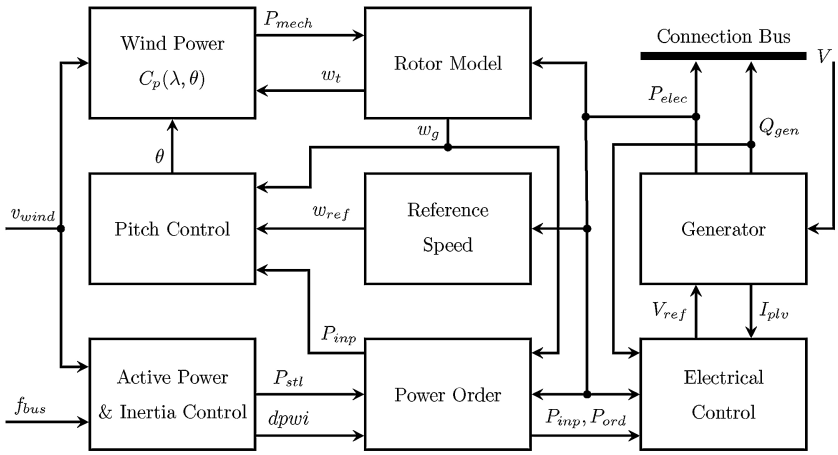

Fig. 1. Connectivity of the model's components.

PhD dissertation [22] for more details. In this paper, we built a full model to the WTG complex control system that is implementable by Matlab ODE15s and other stiff differential equations solvers. Our model then is validated vs. real measured data and [13]. Section 2 of this paper covers this point.

2) Throughout the literature (based on our up to date research), we found sparse and rare academic analysis/discussion for the so-called Q Droop function, suggested by GE [5]. While the concept of the Q Droop function has been widely used in the major commercial tools for the second generation generic models for wind and PV plants, it has always been considered in a feedback platform that usually is not clearly explained or analyzed. GE in [5], extended the brief discussion about Q Droop function, and provided new information (compared to [4]) that this function can be also a “constant” and that the gain parameter of the feedback can be tuned/changed. Also, they mentioned that this function can help enhancing the reactive power control performance, all these claims without any documented analysis or further investigations. Note that such documentation has to exist because the state of the art now is to study the WTG as a member in a compound of WTGs, while all of them are interacting with each other. This has been shown to allow WTGs to exploit the available resources in a better way (see [23]). In this paper, we investigate every aspect of the Q Droop function and its effect on the reactive power control and the entire system performance, especially in extreme cases, such as sudden change in wind, voltage or impedance. Section 3 of this paper covers this point.

3) In [5], there are limiters (control limits) on the different control blocks (including the integrators of the reactive power control) and some derivatives of the mechanical state variables. However, no discussion was provided for how the imposed control limits on the integrators, state variables, and derivatives would behave in extreme scenarios or even local disturbances. Simulations and tests for the control limits need to be conducted. This can lead to a better utilization of the control limits and the simulators, as one can relax or tighten the limits based on better understanding of such limiters. Section 4 of this paper covers this point.

2. The mathematical model

In this section, we build a full time domain mathematical model that can be used by stiff numerical solvers of differential equations (such as ODE15s solve in Matlab). This should allow for deeper and better control studies since the WTG system is highly nonlinear. Also, having the system in time domain allows for non-autonomous simulations that are more practical to present the different scenarios. In order to do that, we explain the control blocks and translate them to differential equations and provide parameter values, C_p coefficients values, and limiters values (control limits). Then we provide a solution to the algebraic equation (the network equation), which results in a system of differential equations instead of a system of differential-algebraic equations, allowing for simpler implementation within numerical solvers. The proposed DFIG-based model includes the Q Droop function and includes most of the controls involved in the WTGs system. Lastly, we compare our model with some other models and validate it vs. real time measured data from a WTG.

In our study, the main citations referenced while building the model were [4,5,13,15–17]. In [4], the block diagrams cover the wind power extraction model, rotor model, pitch control, and reactive power control in both the cases power factor and supervisory voltage were provided. In [5], C_p curves are discussed in more detail and two optional control blocks are added (active power and inertia controls). The GE team in [5] included the Q Droop function. The paper [13], built their model citing [8] and GE studies. The stability of the system was studied in [16], concluding that there is a Hopf bifurcation for small values of the reactance X, which matches and better describes what [13] concluded. We will use the case of a sudden drop in the reactance X as an extreme scenario based on what both [13,16] concluded.

2.1. The block diagrams and state variables

We summarized the model blocks and the dynamics between them in Fig. 1, as it shows the primary components of the model as explained in [4,5,13,15]. Units are Per Unit (pu) except for the pitch which is in degrees.

The wind power model: The power extracted by the turbine is the power in the air-stream multiplied by C_p. As mentioned in [5], $C_p(\lambda,\theta)=\sum_{i=0}^{4}\sum_{j=0}^{4}\alpha_{i,j}\theta^i\lambda^j$ where the tip ratio is $\lambda=\frac{K_b w_t}{v_{\text{wind}}}$, θ is the pitch angle, and K_b is a constant. Fig. 2 shows the C_p function for some fixed values of θ. In the case $v_{\text{wind}} > 11.4$ m/s, θ will be in action,

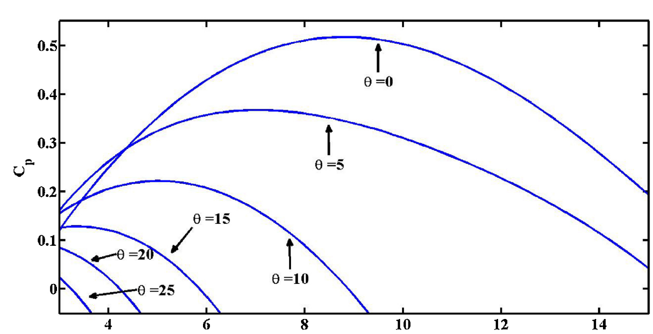

Fig. 2. C_p curves for some fixed values of θ.