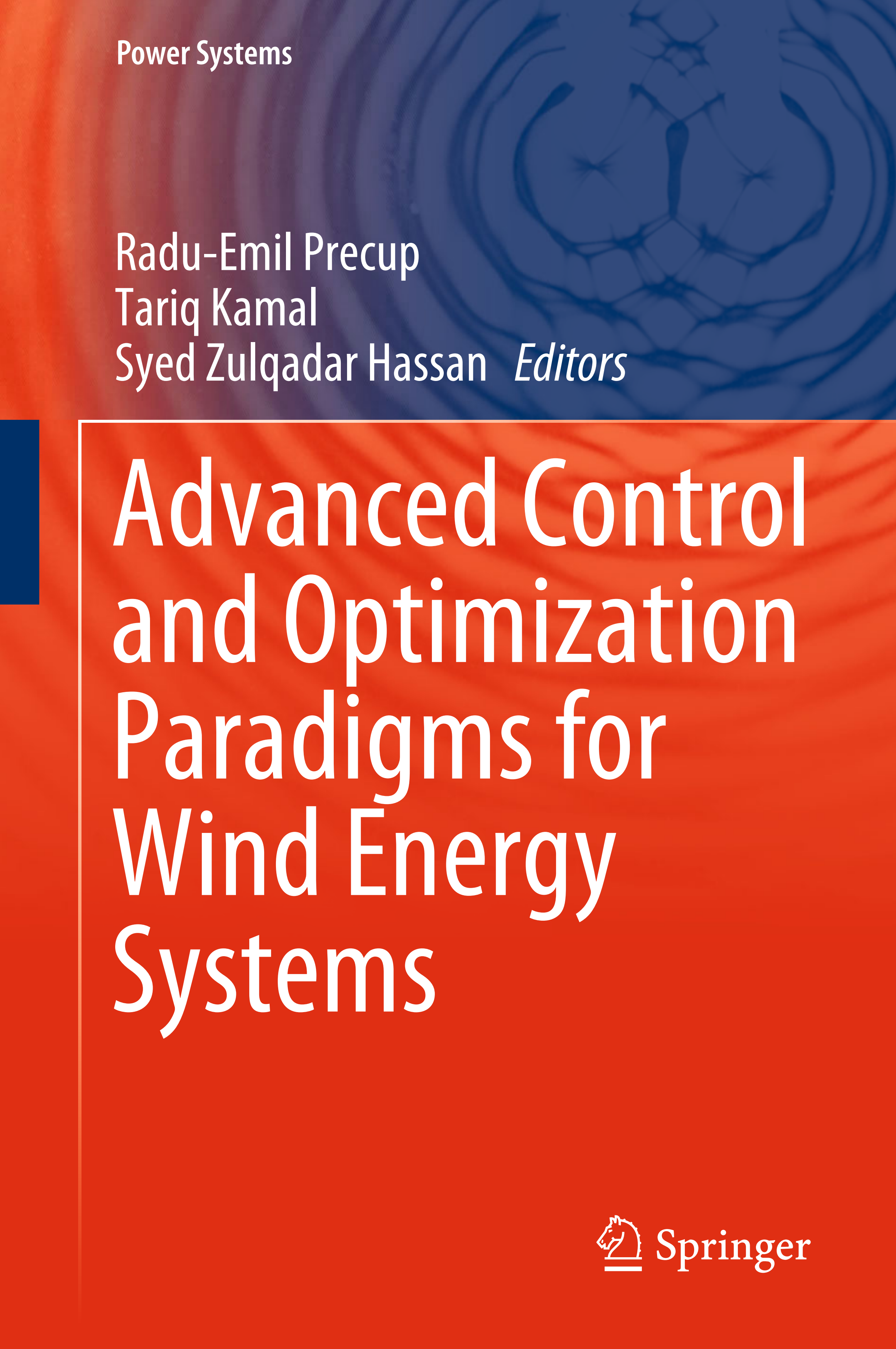
Power Systems



Radu-Emil Precup
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Advanced Control and Optimization Paradigms for Wind Energy Systems

Springer

Power Systems

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Preface

As a kind of sustainable energy source, wind energy systems have received a substantial jump in power industry and currently the fastest-growing (about 30% annually) energy source worldwide as compared to other renewable energy sources. The main concern regarding wind energy systems is the major difference between the highly intermittent nature of the primary source (wind speed) and the desired demands concerning the electrical energy quality and system stability. This leads to challenging control problems because of several types of disturbance inputs. Therefore, wind energy conversion within the standard parameters imposed by the energy market and power industry is unachievable without the essential involvement of optimization and control. Control and optimization techniques have already exposed their importance in all areas of engineering including energy and sustainability. This book uses the rapid growth of control and optimization paradigms (i.e., adaptive control, fuzzy control, artificial neural networks, modified neural-fuzzy control, predictive control, genetic algorithms, and swarm intelligence algorithms) to increase the conversion efficiency, mechanical reliability, dynamical stability, harmonics mitigation, power regulation, and quality in wind energy systems.

The material of the book is organized in the following ten chapters. All chapters are included in this book after a rigorous review process. Special importance is given to chapters offering novel control and optimization techniques in wind energy systems. The contributed chapters provide new ideas and approaches, clearly indicating the advances made in modeling, analysis, and simulation with respect to the existing state-of-the-art.

Chapter "Nonlinear Modeling, Analysis and Simulation of Wind Turbine Control System With and Without Pitch Control as in Industry" of this book provides nonlinear modeling, and simulation of wind turbine generator dynamics and control with and without pitch control. The modeling part is a comprehensive time-domain layout of the model currently considered by industry, such as General Electric and National Renewable Energy Laboratory. The chapter also summarizes some of the most recent and important observations, such as parameter sensitivity, dynamical stability, and multiple timescales structure found in wind turbine generator system. A data validation for the model versus real measured data of the power–wind curve is also discussed and magnifies the findings of this chapter.

Chapter "Distributed Cooperative Control of Wind Farms with On-site Battery Energy Storage Systems" presents research on output power regulation in wind farms consisting of doubly fed induction generator wind turbines equipped with on-site battery energy storage systems. A novel distributed control strategy based on the leader–follower consensus theory is proposed where a virtual leader is embedded in the wind farm supervisory controller to provide the demand information. A small-signal model of a wind turbine and battery energy storage systems is derived, and eigenvalue analysis is conducted to investigate the stability of the combined system.

Frequency regulation in a power system is always critical for the better-quality power supply to the end user. The growth of wind generators and the unpredictability and variability associated with the resource increase the difficulty level of the frequency regulation tasks in power systems. Chapter "Sensitivity Analysis of Frequency Regulation Parameters in Power Systems with Wind Generation" is devoted to study the impact of fluctuating different system parameters on the overall performance of the traditional frequency regulation system when including contributions of wind energy mix. A model for the inclusion of variable-speed wind turbines in the frequency control loops is analyzed, and parametric sensitivity functions are established using linearized models. The stability analysis for inertia sensitivity of frequency regulation involving wind generation is also carried out.

Among the various power quality problems, harmonic distortion is another important problem of power quality in wind energy systems. This phenomenon can cause serious effects on the grid connection, which may result hosting capacity limitation to preserve the overall performance of the network. Chapter "Wind Turbines Integration into Power Systems: Advanced Control Strategy for Harmonics Mitigation" provides physical factors responsible for harmonic current emissions by full-converter wind turbines. The chapter also presents an advanced control structure to mitigate the harmonics in a wind power generator. The design is directed toward guaranteeing the integration of a large-scale wind farm, through minor changes to the background harmonic distortion at the busbar common coupling into the existing electrical grid.

Among the various control strategies, finite control-set model predictive control strategy has emerged as a simple and promising digital control tool for electric power conversion systems. The predictive control is a nonlinear control method and provides an approach that is better suited for controlling power converters in wind energy systems. Chapter "Power Conversion and Predictive Control of Wind Energy Conversion Systems" presents power conversion systems and predictive control strategies for variable-speed wind energy systems. Various forms of predictive control techniques such as predictive current control, predictive torque control, and predictive power control are discussed considering variable-speed wind energy systems as case studies. The predictive control strategies fulfill various control requirements such as maximum power point tracking, regulation of DC link voltage, grid synchronization, generation of reactive power to three-phase grid, and fault ride-through operation.

Chapter "Adaptive Guaranteed Performance Control of Wind Energy Systems" discusses an adaptive guaranteed performance controller for wind energy conversion system equipped with a doubly fed induction generator. The proposed controller consists of outer loop control concerning the aero turbine mechanical subsystem, and inner loop control concerning the electrical subsystem. The proposed technique is capable of quantifying and further guaranteeing the system performance on both transient and steady-state stages with the help of error transformation techniques. The stability is guaranteed through standard Lyapunov synthesis.

Chapter "Machine Learning and Meta-heuristic Algorithms for Renewable Energy: A Systematic Review" presents a detailed review on the application of machine learning and meta-heuristic optimization algorithms in renewable energy. The chapter discusses artificial neural networks, back-propagation neural networks, fuzzy logic, adaptive neuro-fuzzy inference systems, genetic algorithms, swarm intelligence algorithms (including cuckoo search, artificial bee colony, and particle swam optimization algorithms), and their application in wind energy systems.

Chapter "Design of a Supervisory Control System Based on Fuzzy Logic for a Hybrid System Comprising Wind Power, Battery and Ultracapacitor Energy Storage System" presents a control strategy for the coordinated operation of a wind power generator, and battery/ultracapacitor. The proposed control scheme is based on the use of fuzzy logic to monitor the state of charge of the storage systems, while defining their power references to comply with an imposed grid demand. The control strategy is evaluated through simulation under different operating conditions, proving a satisfactory regulation of the monitored parameters and an adequate supply of the grid requirements.

Chapter "Neural-Based P-Q Decoupled Control for Doubly Fed Induction Generator in Wind Generation System" introduces the robust decoupled control of active and reactive powers of a wind-driven doubly fed induction generator using artificial neural network under fault conditions and varying wind speed conditions. The power estimators based on neural networks are trained by back-propagation method, and they are divided into five subnets, namely real and reactive power measurement, reference active and reactive computation, reference stator current computation, reference rotor current computation, and reference rotor voltage computation.

Chapter "An Indirect Adaptive Control Paradigm for Wind Generation Systems" describes an indirect adaptive wavelet-based control to acquire maximum power from variable-speed wind turbine. The new developed controller maintains its self-adaptive behavior under uncertainties generating from various load disturbances and wind speed variation. The proposed technique is better in terms of efficiency, output power, and steady-state characteristics as compared to the existing state-of-the-art.

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Nonlinear Modeling, Analysis and Simulation of Wind Turbine Control System With and Without Pitch Control as in Industry

Sameh A. Eisa

Abstract This chapter introduces the state-of-the-art modeling, analysis and simulation of the wind turbine dynamics and control. The modeling part is a comprehensive time domain layout of the model currently considered by industry, such as General Electric, National Renewable Energy Lab and other major manufacturers. The time domain modeling allows for nonlinear and optimization studies for the highly nonlinear and complex wind turbine control system. Also, this allows for better understanding and intensive study of the very important Pitch control, which is crucial in wind turbine systems, for building/designing control strategies and for optimization objectives. This chapter also provides a documentation for what have been published recently (2016–2018) regarding important dynamical properties and parameter sensitivities in the wind turbine control system. In this regard, the chapter also provides a possible reduction to the wind turbine control system based on the range of wind speeds the wind turbine is exposed to. This allows scholar to study the wind turbine dynamics and control in three different regions, one of them has the Pitch control activated in the case of higher wind speeds. Moreover, the chapter provides an illustration of the dynamical stability and the possibility of approximating the wind turbine control system by multiple time scales. Additionally, The chapter provides different simulations of the system, which can be helpful for academic studies that intend to run non-autonomous scenarios. Also, we cite in a recently (2018) published work, a data validation for the model versus real measured data of the power-wind curve, which magnify the findings of our study.

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List of Symbols

P_{wind}	wind power in the airstreams
ρ, A_r, v_{wind}	air density, rotor area (m^2), wind speed (m/s)
C_p, P_{mech}	aerodynamic power coefficient, power extracted by the turbine
w_{ref}, P_{elec}	rotor reference speed, electrical (active) power delivered to the grid
V	the magnitude of the terminal voltage
R, X, E	infinite bus parameters: resistance, reactance, infinite bus voltage
Q_{gen}	total reactive power delivered to the grid
H, H_g	turbine and generator inertia constants
w_0, w_{base}	initial speed, base angular frequency
D_{tg}, K_{tg}	shaft damping and stiffness constants
f_1, f_2	integrals of differences of speeds and powers
P_{stl}, K_{pp}	rated power and Pitch control proportional
K_{ip}, K_{pc}	integral gain and Pitch compensation proportional
θ, K_{ic}	Pitch angle and integral gain
p_{inp}, T_{pc}	power order (subject to modifications) and its time constant
K_{ptrq}, K_{itrq}	torque control proportional and gain
P_{1elec}, T_{pwr}	filtered electrical power and its time constant
V_{ref}, K_{Qi}	reference voltage and its gain
E_{qcmd}, K_{vi}	reactive voltage command and terminal voltage control gain
Q_{droop}, T_{lpqd}	the droop function and its time constant
Q_{inp}	the input to the droop function block
V_{1reg}, T_r	filtered supervisory voltage and its time constant
V_{reg}, T_r	supervisory voltage and its time constant
Q_{wvl}, Q_{wvu}, K_{pv}, K_{iv}	two integrals lead to Q_{ord} and their gains

1 Brief Introduction

Humanity future is depending much on advancement and development of renewable energies. There are many reasons of why we need to expand our energy systems. This is due to economic justifications and environmental concerns. No matter what the reasons are, we require additional understanding of the generation of renewable energies if we are to fully utilize them.

Based on the US department of energy reported [1], wind energy is the fastest growing source of renewable energies. Consequently, we need more studies and research and to fully comprehend the dynamics and behavior of Wind Turbine Generators (WTGs) if we are to gain the most from this valuable resource. Both corporations and governments are highly interested in understanding the challenges of integrating

WTGs with other conventional power systems. Because of the complexities involved in the WTGs implementation, researching control systems, optimization, energy storage, and power generation of WTGs has dramatically increased recently. In this regard, this chapter is intended to provide a state-of-the-art comprehensive modeling effort that should guide scholars working in the research areas mentioned earlier in this paragraph.

The provided modeling effort in this chapter is a summary for the state-of-the-art nonlinear modeling of WTGs control system dynamics. The industry publications, namely General Electric (GE) ones [2, 3], have been intensively investigated in the last two years through the publications [4–12]. These studies converted the model found in GE reports into nonlinear system of differential-algebraic equations, followed by a wide range of analysis and simulation results. The resultant time domain nonlinear model can be reduced based on the wind speed v_{wind} range the WTG is exposed to. This important possibility of reduction to the model, will be covered and presented collectively in Sect. 2. Also, we will summarize some of the most recent and important observations these studies have concluded about the WTG system, such as parameter sensitivity, stability and different time scale structure found in the WTG system. In Sect. 3, the Pitch control and its significance will be presented. Additionally, some non-autonomous simulations for the given model under Pitch control, is provided. In the same section, we will provide a Simulink verification of the model and how it compares to National Renewable Energy Lab [13, 14]. In this regard, it is important to mention that our modeling intensive study recognized some other modeling sources such as [15–18]. Also, at the end of this chapter, we will provide and discuss a real data validation for the power-wind curve of our model. These verifications and validations are a supportive evidence that the modeling effort presented in this chapter is reliable. This is essential in any optimization or control study. The reader is recommended to check the Ph.D. dissertation [19] for more detailed information about the topics covered in this chapter.

2 State-of-the-Art Nonlinear Modeling of WTGs

In this section, we provide a mathematical model that is in time domain (can be solved by stiff differential equations solvers such as ODE15s in Matlab). This full scale modeling allow for better and more in-depth control studies. This is especially true because the WTG system is highly nonlinear. Also, a system/model formulated in time domain, usually provide better framework for non-autonomous simulations, keeping in mind that non-autonomous simulations are more practical to present extreme scenarios. We start by explaining the different controls in WTGs and translate them into differential equations. Then, we provide tables that summarize and collect the parameters, C_p coefficients, and limiters (control limits) needed for the model. Also, we give a method to eliminate the algebraic equation resulting from the network equation. This results in a system of differential equations instead of a system of differential-algebraic equations, which allows for simpler implementation in numerical solvers.

The main references used while constructing the model are [2–6, 18]. In [2], the control blocks are consistent of the wind power extraction block, one/two mass block, Pitch compensation control block, and reactive power block (power factor and supervisory voltage cases). In [3], C_p curves are provided and explained. The GE team suggested an extra two optional blocks to, possibly, be added (active power and inertia blocks). The GE team in [3] introduced the so called Q Droop function, which has been intensively studied in [6] and fully analyzed in [11]. The study [18] introduced their model effort citing [20] and GE studies. The reader may ask a legitimate question: Why and how GE models relate to other WTGs? In another words, how building the model is inclusive to the-state-of-the-art modeling efforts if it follows heavily GE modeling? These questions were answered by detail in [4–11]. The answers though can be grouped in the two points below:

1. The GE team made the case in their reports [2, 3] that their model can be used to represent WTG models for other manufacturers/companies. As a matter of fact, they have provided many validation results, as can be found in [21].
2. In [8], it is shown that the GE modeling is equivalent to the NREL [13] if we fix the parameters. The Simulink projects used for this comparison are also given in Sect. 3.4. Additionally, we provide in Sect. 3.4 a discussion regarding the data validation for the proposed model (uses intensively GE) versus the model of [18, 20].

2.1 Main Outline of the Model

- Wind power model: Using basic physics, the wind power in the air streams is given by $P_{wind} = \frac{1}{2}\rho A_r v_{wind}^3$ Per Unit (pu), see [3]. This block models how a WTG extracts power from the air and with what efficiency. The model's main purpose is to introduce the C_p curves such that the power extracted by the WTG is $P_{mech} = \frac{1}{2}C_p\rho A_r v_{wind}^3$. As discussed in the introduction, and as in [22], the ideal C_p is the Betz limit which is approximately 0.59. No WTG can extract more than the Betz limit of the power available in the air-streams. C_p curves of the three bladed wind turbine (type-3) are better other types for some tip ratios (Fig. 1).
- Rotor model: This model represents the dynamics of the generator and turbine speeds due to the electrical and mechanical torques. The two-mass model has been introduced in [2, 3, 18] while in [23] this block was represented by a single-mass rotor. It can be noticed that GE studies [2, 3] hinted that single mass rotor may be used for simplification. Later (in Sect. 2.2.1) we will mention the representative differential equations for both models. Figure 2 shows the transfer function for this block as in [3].
- Reference speed: This block models how the reference speed is calculated. The reference speed dynamics are dependent on the generated electric power such that

at steady state $w_{ref} = f(P_{elec})$. GE studies [2, 3] mentioned that the reference speed should increase slowly with the generated electric power until it reaches the rated speed. This speed is essential to control the generator and turbine speeds. There is a difference between [2, 3, 18] regarding the transfer function of the reference speed. Later (in Sect. 3.4) we will discuss this difference in more detail.

- Pitch control and compensation: This block captures the dynamics of the Pitch. This has been a growing area of research. This control calculates the Pitch angle based on the differences between the rated power and the power order, and between the reference speed and the generator speed. The Pitch angle has direct effect on power extraction efficiency. This is an important control to keep the WTG producing the rated power for a higher range of wind speeds. Figure 3 shows the transfer function for this block as in [3].
- Reactive power control: This control manages the generated reactive power from the WTG. This control can be in the power factor setup or the supervisory voltage setup. The first case occurs when the WTG is treated as one unit by itself, while the second case occurs when the WTG is treated as one unit in a compound of units. These two cases were introduced in [2, 3, 18]. Figure 4 shows the transfer function for this block as in [3].
- Electrical control: Unlike the previous block where the control was for the reactive branch that feeds the generator, the electrical control shows how the active current can be generated and controlled. This block is the same across the references [2, 3, 18] that covered it. Figure 5 shows the transfer function for this block as in [3].
- Active power and inertia controls: Usually these controls are not activated. The function of these two controls is to manage the power order produced by the WTG. This management depends on and corresponds to changes in bus frequency. The two controls provide extra power in the case there is lower than normal bus frequency (reference frequency) and vise versa. The active power control provide extra power by setting up the maximum rated power and cutting out, if needed, the available power to the WTG. On the other hand, the inertia control does the same function, but by providing extra power from the rotor inertia. GE [3] has hinted that most current WTGs have yet to implement these controls as of 2010. Figures 6 and 7 show the blocks as in [3].
- Converter/Generator model: This is the step where the output the WTG is delivered to the power grid. Two branches are considered in this model, active and reactive ones, which deliver the active and the reactive power to the grid respectively. In [2, 3] this model is very similar, with some lower and upper limit differences for the controls, however, in [18] we see that a third branch is added to the model for the phase shift convergence between the resultant components (current and voltage) of the wind turbine and the grid. For more detail about how this difference is insignificant when we have stability, the reader is recommended to read about the convergence between the models in [19]. Figures 8 and 9 show the generator model as in [2, 18] respectively (Fig. 10).
- Terminal voltage and grid model: The terminal voltage is the connection between the converter/generator model and the grid model. In the models we follow, the wind turbine is connected to the grid in order to work. This implies that even for

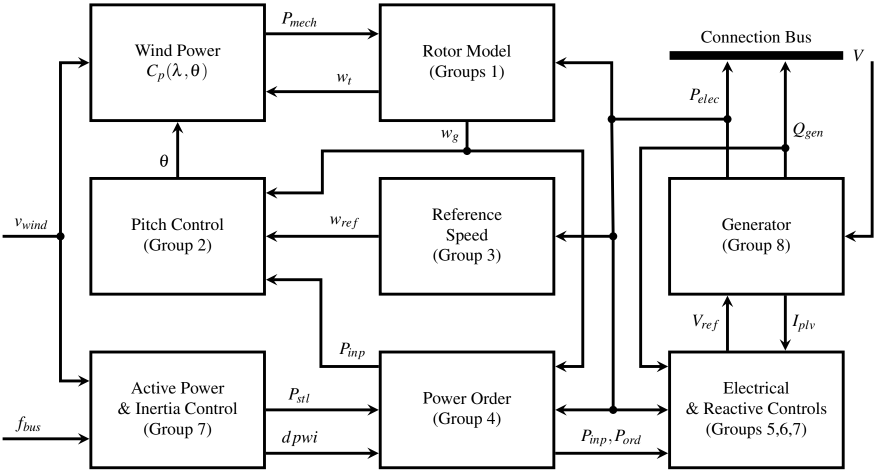


Fig. 1 WTG control blocks and dynamics

theoretical/mathematical studies, the grid should be modeled so we can have an algebraic equation (the network equation) from Kirchhoff's law, that relates the dynamics of the WTG to the grid. In our study, we follow the model used in [18] and suggested in [2, 3] to represent the grid by an infinite bus model, see Fig. 11. Therefore, the terminal voltage will be given by the following equation as in [18]:

$$(V^2)^2 - [2(P_{elec}R + Q_{gen}X) + E^2]V^2 + (R^2 + X^2)(P_{elec}^2 + Q_{gen}^2) = 0 \quad (1)$$

Note that, if the grid model changes to another model other than the infinite bus, a new algebraic constraint will need to be derived and analyzed. Without this part of the grid modeling, the wind turbine is working without load and has undefined inputs to some of the control dynamics. Figure 12 gives the transfer functions of the WTG as in [3].

2.2 *Characteristics and Dynamical Analysis*

2.2.1 Translating the Blocks of Transfer Functions and Controls into a System of Differential Algebraic Equations

Having first reviewed the transfer functions and control blocks in Sect. 2.1, we now begin the process of breaking down the blocks (in every Fig.) into algebraic relations in the transfer function domain. This will be done by deriving the transfer function relations after specifying nodes of variables.

Group 1: Two mass model as in Fig. 2.

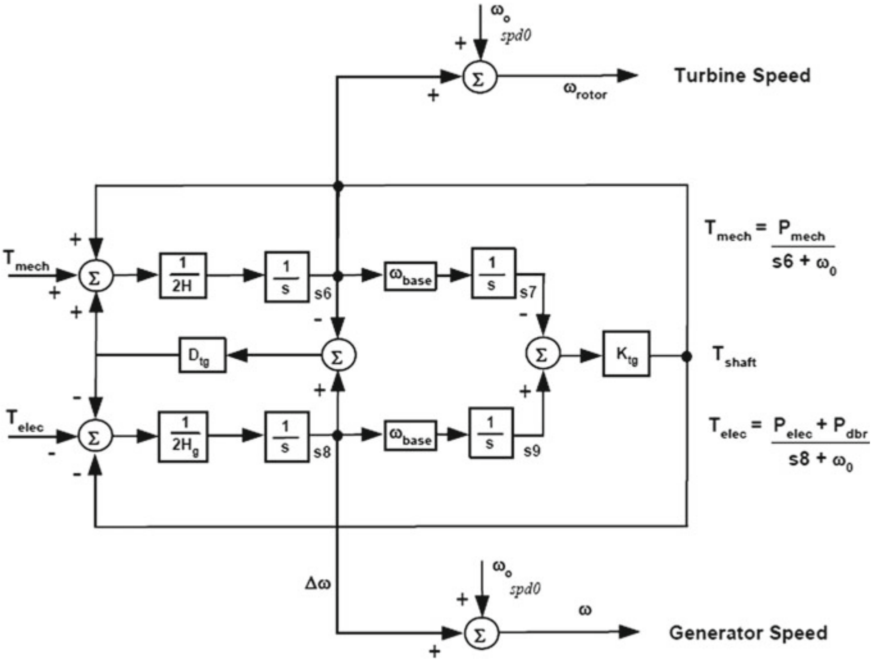


Fig. 2 Two mass model of a WTG as in [3]

In Fig. 2, we let the nodes $s_6 = w_g$ and $s_8 = w_t$, so the turbine speed will be the sum of w_0 and the node s_6. Therefore, $w_{turbine} = w_{rotor} = w_t + w_0$ and similarly the generator speed $w_{generator} = w = w_g + w_0$. Also we let $\Delta\theta_m = s_9 - s_7$, so $T_{shaft} = K_{tg}\Delta\theta_m$. Thus w_t is given by,

$$w_t = \frac{1}{2H} \cdot \frac{1}{s}[T_{mech} + D_{tg}(w_g - w_t) + T_{shaft}]. \tag{2}$$

Similar to Eq. (2) we get,

$$w_g = \frac{1}{2H_g} \cdot \frac{1}{s}[-T_{elec} - D_{tg}(w_g - w_t) - T_{shaft}] \tag{3}$$

and,

$$\Delta\theta_m = \frac{w_{base}}{s}(w_g - w_t). \tag{4}$$

The above equations contain the dynamics of the two mass rotor model.
Group 2: Pitch control as in Fig. 3.

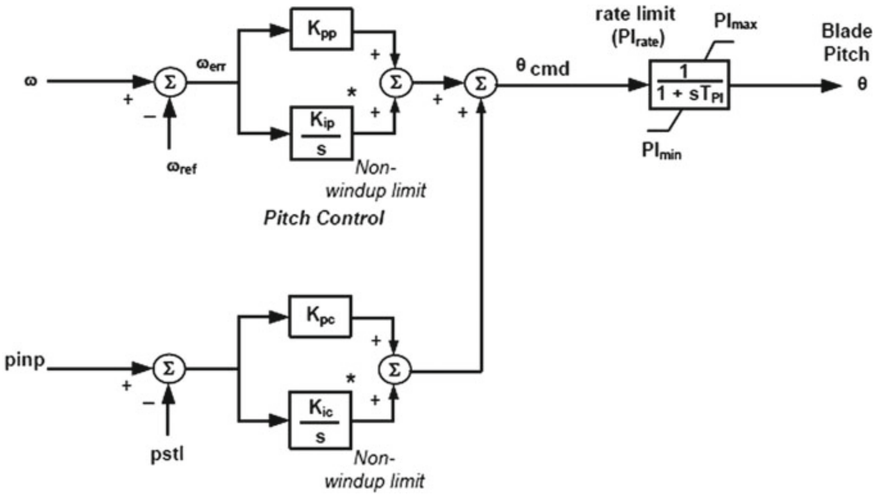


Fig. 3 Pitch control model of a WTG as in [3]

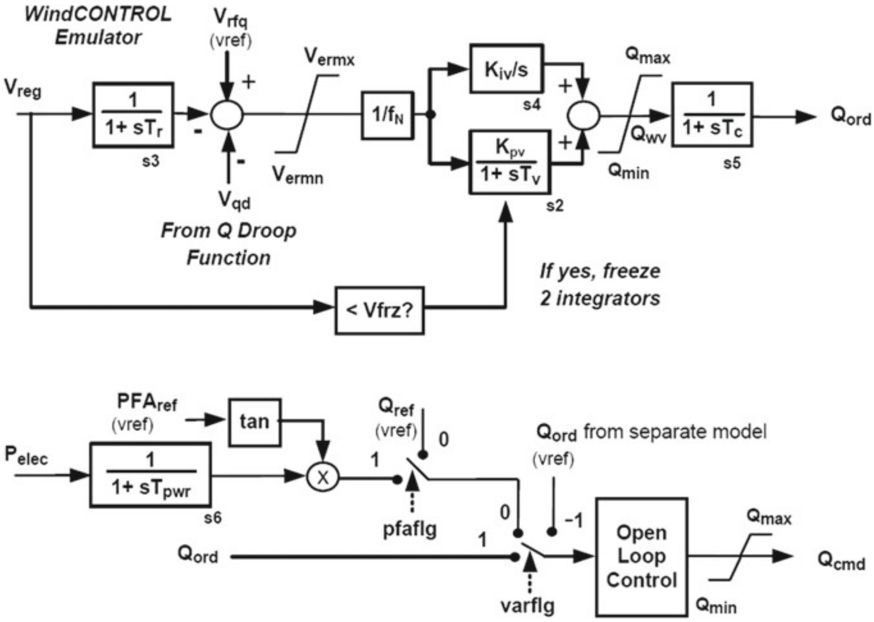


Fig. 4 Reactive power control of a WTG as in [3]

In Fig. 3, we start with the two integrators (branches that have $\frac{1}{s}$). We let f_1 be the output of the transfer function $\frac{K_{ic}}{s}$ and we let f_2 be the output of the transfer function $\frac{K_{ip}}{s}$. Thus,

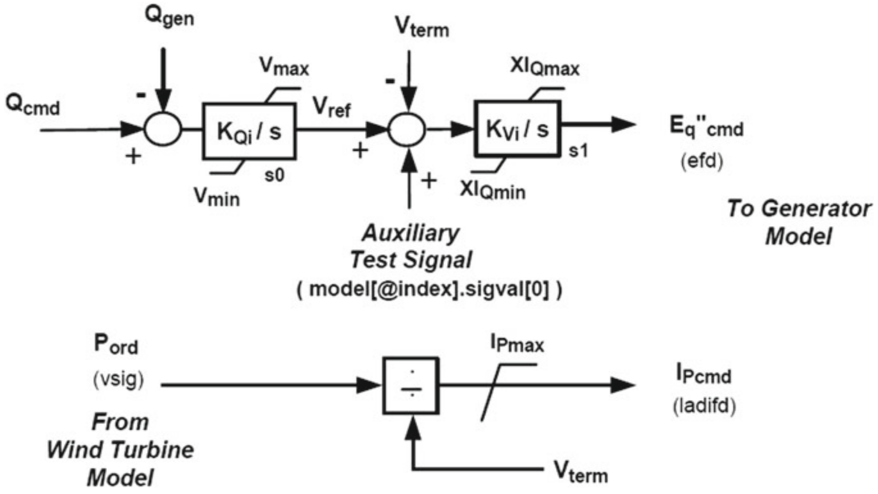


Fig. 5 Electrical control of a WTG as in [3]

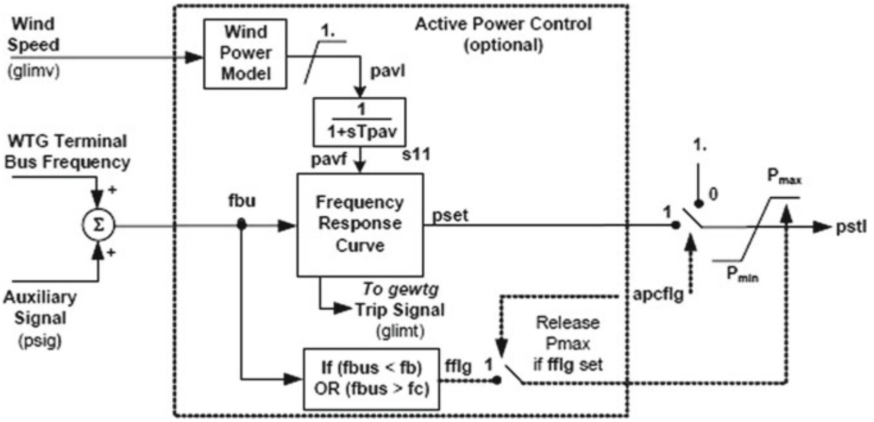


Fig. 6 Active power control of a WTG as in [3]

$$f_1 = \frac{(w - w_{ref})}{s} = \frac{(w_g + w_0 - w_{ref})}{s} \tag{5}$$

and,

$$f_2 = \frac{(P_{inp} - P_{stl})}{s}. \tag{6}$$

The Pitch angle command (θ_{cmd}) is the node after summing the upper and the lower outputs of the Pitch control. Also, it is the node before the transfer function of T_{pl}. Thus θ_{cmd} is given by,

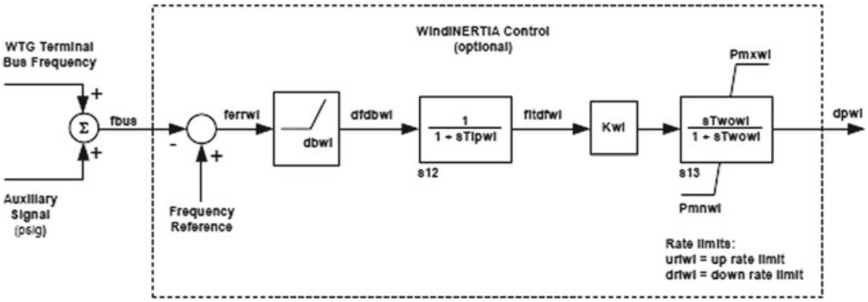


Fig. 7 Inertia control of a WTG as in [3]

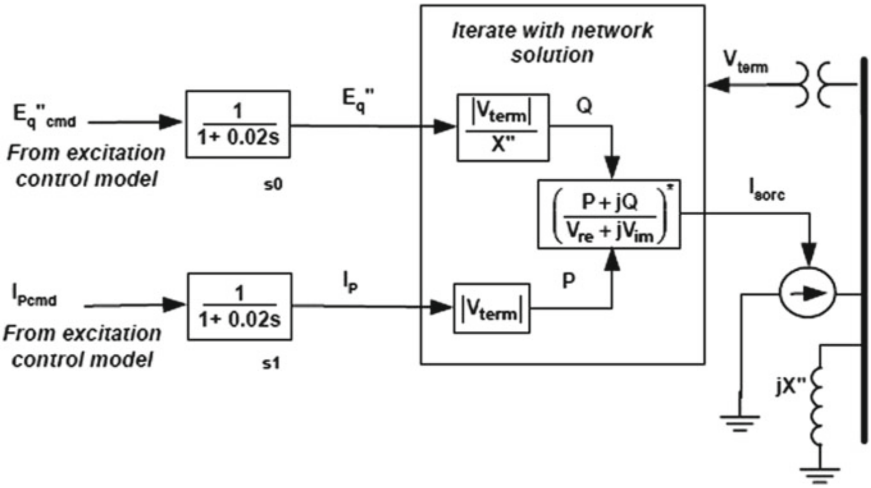


Fig. 8 Converter/Generator model of a DFAG/DFIG WTG as in [2]

$$\theta_{cmd} = K_{pp}(w_g + w_0 - w_{ref}) + K_{ip}f_1 + K_{pc}(P_{inp} - P_{stl}) + K_{ic}f_2. \tag{7}$$

The Pitch angle (θ) is the output of the transfer function of T_{pl}, which has θ_{cmd} as an input. Thus θ is given by,

$$\theta = \theta_{cmd}\frac{1}{1 + s \cdot T_{pl}}. \tag{8}$$

After algebraic re-arrangement we get,

$$\theta = \frac{K_{pp}(w_g + w_0 - w_{ref}) + f_1 + K_{pc}(P_{inp} - P_{stl}) + f_2}{1 + s \cdot T_{pl}}. \tag{9}$$

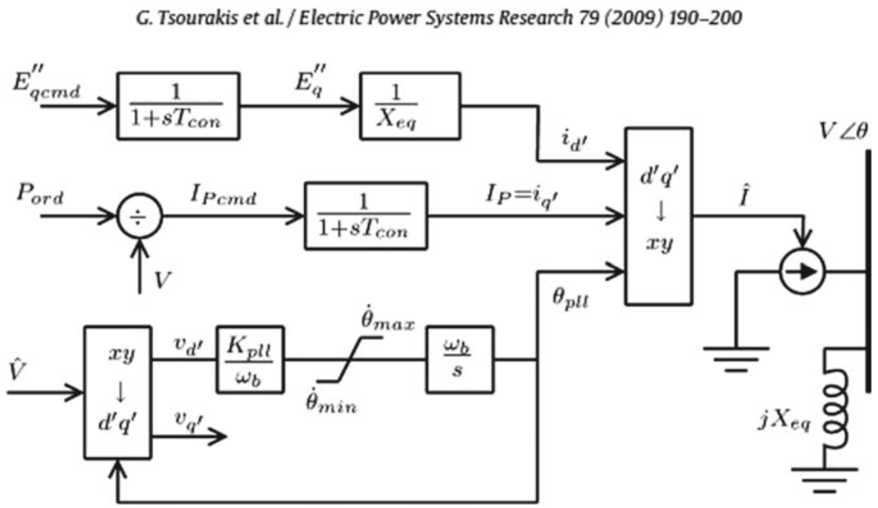


Fig. 9 Converter/Generator model of a DFAG/DFIG WTG as in [18]

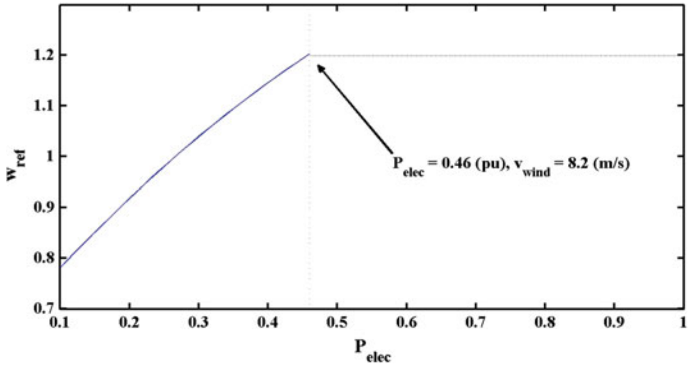
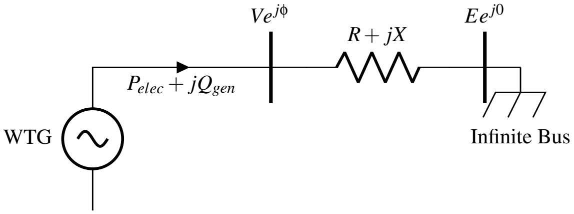


Fig. 10 w_{ref} steady state as a function of P_{elec} as in [4]

Fig. 11 Single machine infinite bus test system as in [4]



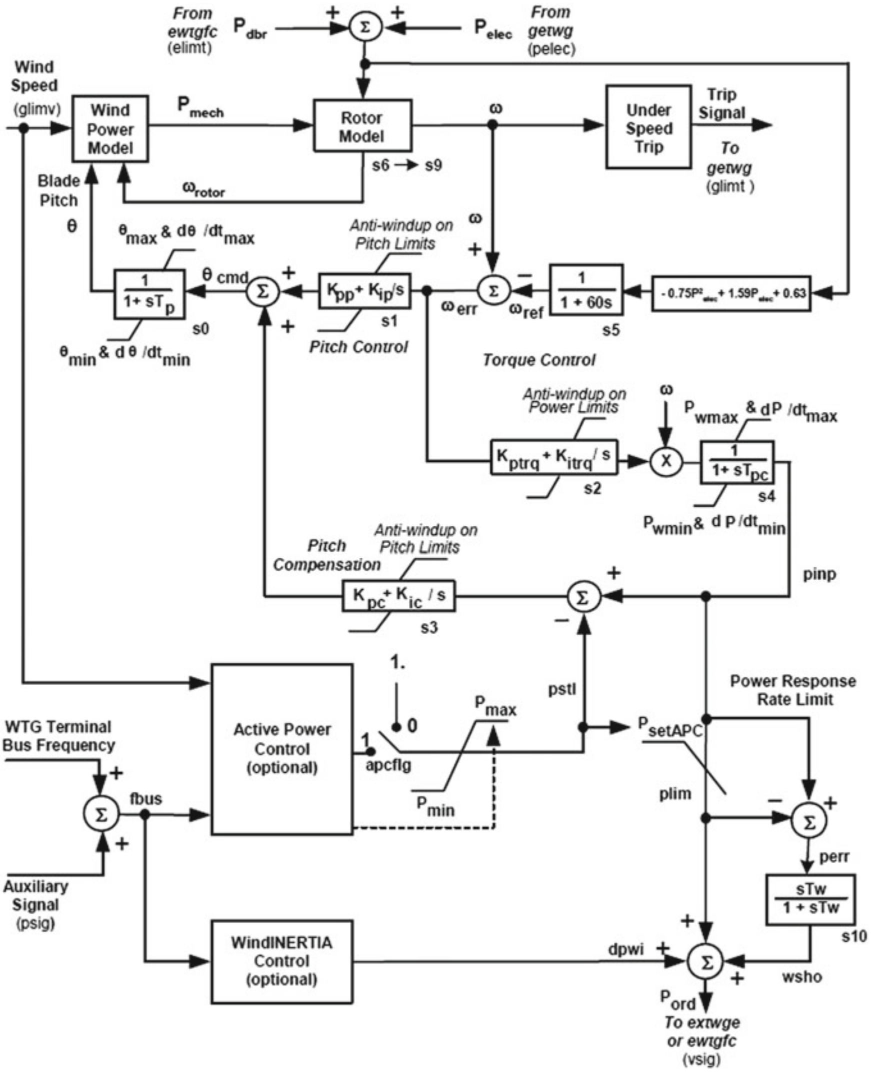


Fig. 12 All of the WTG model transfer functions and controls as in [3]

Equations (5), (6), and (9) contain the dynamics of the Pitch control.

Group 3: Reference speed as in Fig. 12.
The reference speed w_{ref} is the output of the transfer function $\left(\frac{1}{1+s\cdot 60}\right)$, which has the node symbol s_5 (at the upper part of Fig. 12). The input for this transfer function is $-0.75P_{elec}^2 + 1.59P_{elec} + 0.63$. Thus w_{ref} is given by,