Abstract

As the proportion of renewable energy continues to rise globally in response to climate change concerns, European Union transmission system operators (TSOs) have outlined specific requirements for generators in the latest Network Code for Requirements for Generators (NC/RfG). These requirements emphasize the active contribution of integrated generating units to grid stability by engaging in frequency and voltage control. Moreover, these units are expected to transition from grid-following to grid-forming operations when feasible.

The growing integration of offshore and onshore wind farms has introduced challenges to frequency stability due to power imbalances stemming not only from load variations but also from fluctuations in wind power. To address this, wind turbines (WTs) and other renewable energy sources must regulate their output power to mitigate generated power fluctuations and support frequency stability. However, commonly used wind turbines with doubly fed induction generators (DFIG) face limitations related to rotor speed, converter power, and power output variations due to wind speed fluctuations and model-plant mismatches.

Transmission system operators (TSOs) must adapt the operation modes of wind turbines, necessitating accurate estimation of available power to ensure optimal set-point assignments. This thesis proposes a comprehensive three-step strategy for the optimal integration of wind turbines into the grid, aligning with the latest grid code requirements for providing grid support services.

The first step involves employing a Model Predictive Estimation (MPE) algorithm to accurately estimate wind turbine available power. This estimation facilitates TSOs in providing optimal operation set points to each wind turbine based on reserved power at each time step.

The second step employs Model Predictive Control (MPC) at the TSO level, utilizing accurate wind power and load status information to provide each connected wind turbine's rotor speed controller with an optimal operating point. This includes determining the de-loading ratio to address wind disturbances. Additionally, the TSO can switch between grid-following and grid-forming modes based on power availability and load levels. A grid-forming controller is introduced to emulate conventional generators' synchronizing and load-sharing properties, considering rotor speed and side converter limitations.

In the final step, the power coefficient set-point and rotor speed set-point are translated internally within the wind turbine's local speed controller using the MPC control strategy.

The thesis also delves into the stability of current and future power systems with non-uniform generators, acknowledging the challenges posed by non-homogeneous dynamics, control strategies, and intermittency. To address these issues, the thesis introduces the Data-enabled Predictive Control strategy (DeePC), showcasing its ability to learn the dynamics of an unknown power system directly from measurements and optimize active power injection. This results in a significant improvement in grid frequency support and stability, avoiding the need for a parametric system representation. Simulation results demonstrate the effectiveness of DeePC compared to conventional strategies in enhancing frequency control.

Chapter 1

Introduction

1.1 Motivation and background

With the rapid integration of wind turbines into power systems, a considerable increase has been allocated for wind power. Despite the advantage of supplying the grid with green energy from wind, transmission system operators (TSOs) are beginning to face stability issues in their power systems due to the transition from synchronous generators (SGs) to large wind farms. These wind farms are associated with a variety of generated power profiles due to varying wind conditions [1]. Hence, the risk of compromising the stability of the grid has become the focus of many researches. The negative impact of wind turbines (WTs) on grid stability can be summarized in two major points. First, a wind turbine operating in maximum Power Point (MPP) mode adds more oscillation to the grid frequency and strains other conventional generating units (such as hydro power) in balancing power generation and consumption [2]. Second, given that most power converters connected to the grid operate in grid-following mode (GFL), the presence of a robust grid, where synchronous generators (SGs) impose frequency and voltage, is still required to avoid losing synchronization within the power grid. Therefore, to overcome these issues, grid-forming (GFM) strategy has to be considered in some interconnected wind turbines to enhance the reliability of the power grid in case of a sudden outage of SG. In these networks codes (NC RfG EU 631/1447 in 2016 & 1485 in 2017), TSOs have clarified in their frequency defense plan that all existing and newly integrated power-generating units from type C & D (generating units with capacity 50 MW and more) should respond to grid frequency changes by adjusting their output power accordingly. This adjustment applies to both synchronous power-generating modules (SPGM) and renewable power-park modules (PPM) [3]. TSO refers to this service as a frequency containment reserve (FCR). In this regard, many authors suggested modifying the rotor side converter of wind turbines with maximum power point tracking operation (MPPT). This modification aims to achieve short-term support following any frequency event by converting a part of kinetic energy in the rotor to active power and injecting it into the grid or vice versa [4],[5]. In the literature, this modification is referred to as synthetic inertia. However, this temporary frequency support can be reasonable only in a case where the share of conventional generators in the grid are sufficient to take over grid frequency stabilization efforts after any load increase or generator outage scenarios. Based on forthcoming strategies to increase the share of renewable energy generators at the expense of conventional ones, the aforementioned short-term frequency support scenario from WT can be problematic. To bridge the gap between the intended transition to green energy and the lack of power reserve due to the reduction in SGs, some authors have suggested operating wind turbines in de-loading mode instead of MPPT. The de-loading operation can be achieved by converting a portion of the available power from the wind into kinetic energy and storing it in the rotor [6], [7]. In this case, wind turbines, similar to SGs, can increase their output power by converting the additional stored kinetic energy, whether partially or entirely to active power and sending it to the grid when required. This could be achieved mechanically by modifying the pitch controller to follow a power set-point or electrically by adjusting the electrical torque via the rotor side converter of WT. However, it is essential to note that meeting grid code requirements necessitates considering additional factors when implementing primary frequency support features in wind turbines [8], [9]. Some of these points are the response time, available power, quality of power delivered from wind turbines into the grid and the limitations on wind turbine rotor speed and rotor side converter to avoid the unsafe operation of the wind turbine. In addition, the overall stability of the power system with this high prevalence of wind turbines with potential grid service contribution should also be examined and ensured.

1.2 Scope of this thesis

In alignment with the ongoing efforts to augment the share of renewable energy, particularly wind power, this thesis concentrates on optimizing the operation of wind turbines to adhere to the latest grid code requirements. The de-loading operation of wind turbines paves the way for implementing advanced control strategies, enabling wind turbines to operate as effectively as conventional generators in terms of grid frequency support. Data-enabled predictive control strategy is used to address the issues with future power system modeling and ensure an optimal active power control of interconnected generators. Finally, the stability analysis of the overall power system with high penetration of wind power is also investigated and addressed.

1.3 Thesis contribution and outline

The main contributions of the present thesis are fourfold:

- Actual available wind power estimation to enable TSO to formulate the optimal power set-point distribution strategy among generating units for the given load.

- Model predictive control strategy for wind turbines (WTs) to adhere to the TSO power set-point and operate in de-loading mode, considering both grid requirements and wind turbine limitations.
- Implementation of a grid-forming design in the rotor side converter of wind turbines to enhance the reliability of the power system.
- Model-free enabled control for frequency regulation in a non-homogeneous grid with a high percentage of wind power to improve overall grid stability.

1.4 List of Publications

[1] B. M. Melhem, Y. Zhou and S. Liu, ”Frequency Support and Stability Analysis for an Integrated Power System with Wind Farms,” IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, USA, 2018, pp. 159-164, https://doi.org/10.1109/IECON.2018.8592707.

[2] B.M. Melhem and S. Liu, “Adaptive approach for primary frequency support by wind turbines based on grid code requirements and turbines limitations,” 2023 IEEE PES Grid Edge Technologies Conference & Exposition (Grid Edge), San Diego, CA, USA, 2023, pp. 1-5, https://doi.org/10.1109/GridEdge54130.2023.10102734.

[3] B.M. Melhem and S. Liu, “Optimal active power control of wind turbines in grid-forming mode,” 21th International Conference on Renewable Energies and Power Quality (ICREPQ’23) Madrid (Spain), 24th to 26th May 2023, ISSN 2172-038 X, Volume No.21, July 2023.

[4] B.M. Melhem and S. Liu, “Model predictive estimation of wind power for coordinated generation,” 4th International Conference on Smart Grid and Renewable Energy (SGRE2024), Doha/Qatar

[5] B.M. Melhem and S. Liu, “Data-enabled predictive control for frequency control in future heterogeneous power systems,” 4th International Conference on Smart Grid and Renewable Energy (SGRE2024), Doha/Qatar (Best Paper Award),

Chapter 2

Challenges of large-scale wind turbines integration into power systems

This chapter is devoted to elucidating the problem statement addressed in this thesis. It delves into the challenges linked to both present and forthcoming initiatives aimed at extensively integrating wind turbines into the grid. Special attention is given to their direct effects on the resilience of power supply and grid stability. The discussion will encompass the impact of model design, active power control, and operational modes of wind turbines on the stability of grid frequency and synchronization with other generation units. Subsequently, the structure and key points of this thesis will be outlined.

2.1 Power system modeling for frequency analysis

Most studies on frequency oscillations typically suggest an equivalent power system model involving the swing equation. In this equation, all grid generators are amalgamated into a unified rotating mass characterized by an equivalent inertia constant denoted as H_t [10]. The estimation of this H_t is accomplished through:

$$H_t = \frac{\sum_{n=1}^{n} H_i.S_{B,i}}{S_B} \tag{2.1}$$

In this context, H_i represents the inertia constant, and $S_{B,i}$ corresponds to the rated power of synchronous generator i. Here, n stands for the total count of synchronous generators linked to the grid, while S_B denotes the rated power of the entire power system. Consequently, the swing equation for the power system is formulated as follows:

$$\Delta f_g = \frac{1}{(2H_t s + D_t)}(\Delta P_g - \Delta P_L) \tag{2.2}$$

with H_t represents the equivalent inertia of the grid, while D_t stands for the damping factor, capturing the correlation between load power and frequency, and $\Delta P_g, \Delta P_L$ are the deviation in power generation and load, respectively [11]. It does worth noting that there are additional damping elements in a power system, such as speed governing and excitation systems [12].

Fig. 2.1 represents a typical power system topology, which will also be used later for analyzing the synchronization in Chapter 5. It consists of generating units with different dynamics, operation modes, and control strategies connected to four buses and variable loads. This typical topology indicates the non-homogeneity, variety, and geographical distribution of power generation sources, which is the case in the current power systems.

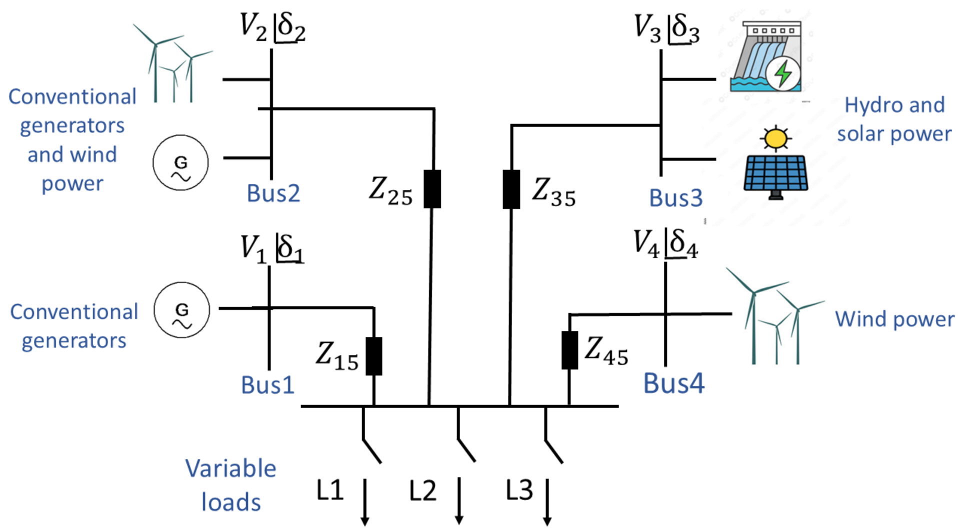

Figure 2.1: Typical modern power systems with different generation sources and distributed loads

Figure 2.2 illustrates the primary components typically considered in power system studies. Within this framework, both conventional and renewable generation units' power systems and generation unit models are employed for frequency control analysis, with a specific focus on wind turbines in this thesis. The generator models outlined in this thesis are linear and based on transfer functions, facilitating the derivation of time-domain responses. Consequently, these models are well-suited for analyzing the system's behavior under small-signal stability.

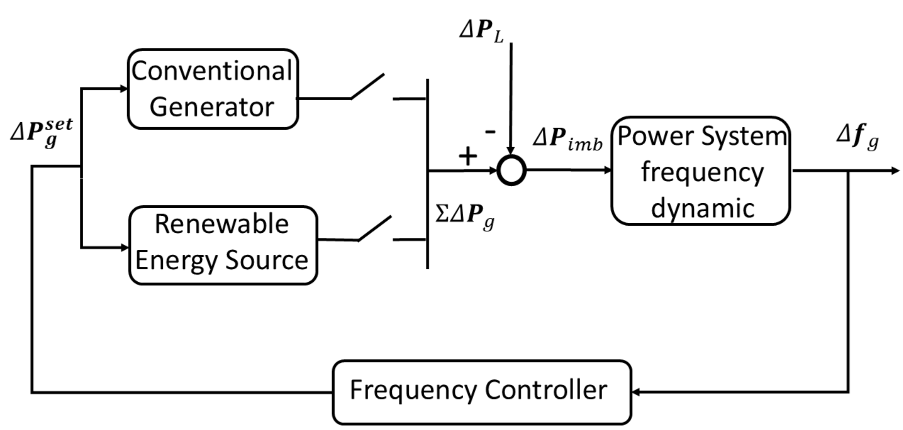

Figure 2.2: General overview of power system with frequency control

The power system model corresponding to Eq. 2.2 is shown in Fig. 2.3.

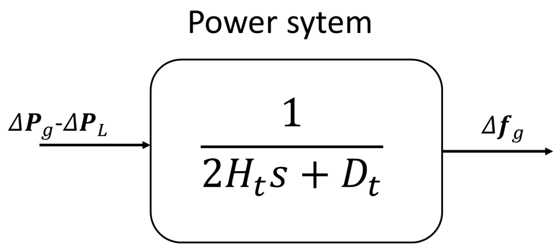

Figure 2.3: Power system dynamic for stability studies

2.1.1 Conventional power plant model

In frequency stability studies, thermal power plants have been traditionally used by TSO for frequency control purposes [13]. As a usual term, thermal power plants mainly refer to those based on fossil fuels: coal, oil, and natural gas [14], which still represent an essential share in current power systems. The block diagram of a conventional generator model is given in Fig. 2.4

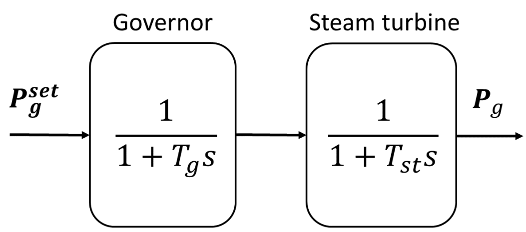

Figure 2.4: Synchronous generator dynamic

P_g^{set} [W] is the set-point power, T_g [sec] is the time constant of the governor, T_{st} [sec] is the time constant of the steam turbine which include the time of steam chest and the inlet piping, and P_g [W] is the generated power.

2.1.2 Wind power plant model

The frequency control based on wind power plants has become a meaningful subject during the last decade [15]. In addition, wind turbine generator design influences the control mechanism being variable wind speed turbine (VWST) is the most common design and allows the implementation of different frequency control strategies or techniques [16-17]. However, these generation units do not sense any grid frequency drop as they are connected to the grid through converters [18], even though wind turbines have similar inertia to conventional generators due to the stored kinetic energy in their rotating masses [19]. Different equivalent wind power plant models have been proposed in the specific literature to provide and evaluate grid frequency stability with high variable RES integration.

The most common model used to simulate an equivalent wind turbine for frequency studies is shown and described in Fig. 2.5

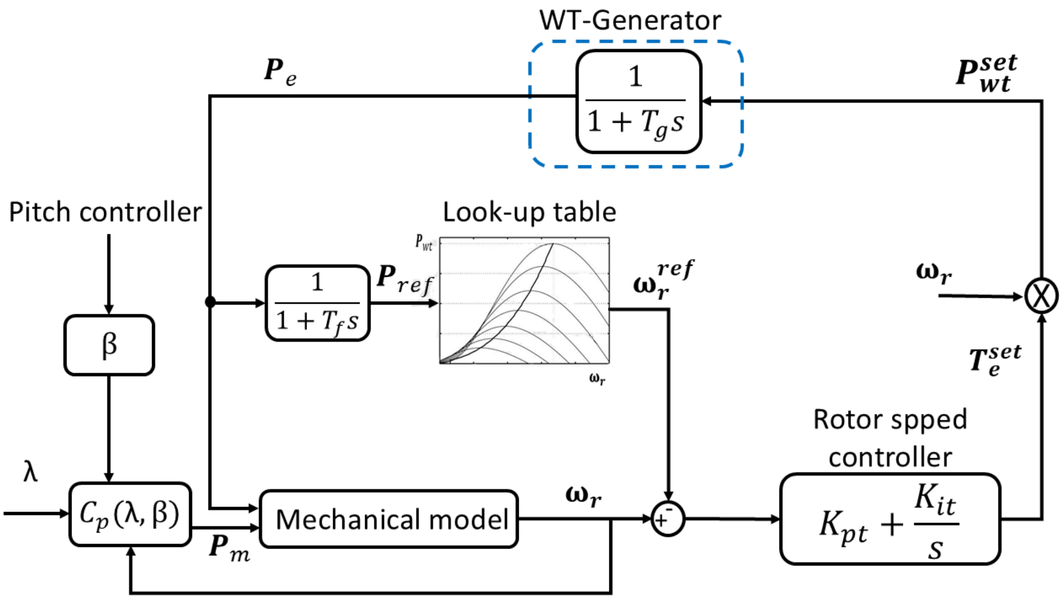

Figure 2.5: Equivalent model of a wind turbine

First, the mechanical model is considered to be a one-mass as follows:

$$\omega_r = \frac{1}{2H_{wt}s}(P_m - P_e) \tag{2.3}$$

with ω_r [rpm], H_{wt} [sec],P_m [W],P_e [W] are the rotor speed, turbine inertia constant, mechanical power and electrical power, respectively.

In addition to the mechanical model, the power coefficient C_p, which is the most critical parameter as it defines the operation point of the wind turbine, can be determined based on the pitch angle β [deg] from the pitch controller of the turbine's blades, as we will as the tip speed ratio (TSR) λ, which is defined as:

$$\lambda = \frac{|\omega_r R|}{v_w} \tag{2.4}$$

with R is the turbine radius in [m], v_w in [m/s] is the wind speed. T_e is the electrical torque applied to the rotor to accelerate or decelerate the rotor speed.

2.2 Operation principle of variable speed wind turbines

Before the late 1990s, the predominant approach among wind turbine manufacturers involved the construction of fixed-speed wind turbine systems (FSWTSs). These