Impact of Wind Generation on Dynamic Voltage Characteristics of Power Systems

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IMPACT OF WIND GENERATION ON DYNAMIC VOLTAGE CHARACTERISTICS OF POWER SYSTEMS

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In recent times there has been an increasing interest in renewable energies due to public awareness of the negative effects on the environment of conventional electricity generation resources like coal and oil, and several policies have been enacted requiring progressive reduction of fossil-fuel-based generation. Due to some favorable characteristics of wind over other renewables, wind power has grown considerably in the last two decades.

Integration of wind generation into the existing power grids poses significant challenges. The limited reactive power capability that wind turbines have can cause several problems, such as important voltage drops or rises in the system. Therefore, dynamic voltage stability is a major concern. This thesis presents an investigation of the voltage characteristics of an electric grid connected to wind generation and subject to fault conditions. A comparison between the dynamic voltage performance of synchronous machines, which are the traditional type of generators, and wind farms has been made. Both type III and type IV wind turbines have been considered, as they are the dominant types in the market.
The New England region possesses abundant potential for developing both inland and offshore wind power generation. However, inland wind resources are mostly in remote locations in Northern New England, far from major load centers. Therefore, long transmission lines are required to connect the wind farm to the rest of the power grid, placing them in a weak point of the system. The present study includes an analysis of the role that the point of electrical interconnection of a wind farm with the rest of the system plays on dynamic voltage performance. The Thevenin impedance seen by the wind bus has been used as a measure of the strength of the connection, and its relation with several variables that characterize the severity of a fault has been determined. The concept of Thevenin impedance has not been used in the literature before to study the dynamic voltage response of a wind farm, and it is proved by this work to be a useful tool for assessing the best option when connecting a wind farm to a power grid.

The IEEE standard 39-bus system, which is a simplified representation of the New England electric grid, has been used as a platform to illustrate the developed methodology. The present study has set the base for extending the analysis to the real New England power system.
DEDICATION

I dedicate this thesis to my family: my parents Javier and Esther, my brother Miguel and my grandmother Marce, for their permanent support and affection and the example of hard work and honesty that they have set for me.
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CHAPTER 1

INTRODUCTION

This Chapter serves as an introduction to the work developed in this thesis. The motivation for conducting this research, along with its objective and the approach taken to reach it are explained. The organization of the rest of the Chapters of the thesis is included at the end of this Chapter.

1.1 Motivation and Background

First, the motivation for developing this work will be explained, summarizing the enormous potential of wind energy but also the challenges that it poses to power systems. These challenges are motivating major research in the area of wind power, given its many advantages.

1.1.1 Wind Energy Opportunities and Challenges

Recently, there has been increasing interest in renewable energies due to public awareness of the negative effects on the environment of conventional electricity generation resources like coal and oil. The United States has enacted several renewable electricity mandates, which are laws that require utilities to sell or produce a certain percentage of electricity from renewable sources. Usually the required percentage of renewable electricity increases over time until reaching a target percentage, such as 20 or 25 percent, at a target year, such as 2020 or 2025. Twenty-nine states have renewable electricity mandates and an additional six states have renewable electricity goals [1]. Due to some favorable characteristics of wind over other renewables, wind generation has grown considerably in the last two decades [2].
The New England region, which comprises of six states in the northeastern corner of the US, possesses abundant potential for developing both inland and offshore wind power generation. The New England Wind Integration Study showed that up to 12,000 MW could be generated using this renewable source, as compared to the existing generating capacity of 800 MW [3], [4]. This same study pointed out that the region could generate up to 24% of its total annual electric energy needs in 2020 using wind power, given that certain transmission upgrades are performed. Most of New England’s wind resources are located in the state of Maine, where Maine’s Renewable Electricity Mandate set a goal for 8,000 MW of installed wind capacity by 2030, which implies a significant rise compared to the 600 MW of current wind generation [5].

It is important to point out that inland wind resources are primarily in remote locations far from major load centers, particularly in the Northern New England region, as shown in Figure 1.1. Therefore, long transmission lines are required to connect the wind farm to the rest of the power grid, placing them in a weak point of the system. As opposed to other generation resources like nuclear or gas, whose location can be chosen by the system planners, the location of a wind farm is selected primarily based on good wind conditions, although it is also subject to environmental and economic constraints [6], [7].
As summarized in the previous paragraphs, wind generation has great potential, particularly in the New England region. However, integrating wind generation into the existing grid poses some significant challenges from the electrical point of view, particularly due to the limited reactive power capability that wind turbines have. This can cause several voltage problems, such as important voltage drops or rises and fluctuation at the point of connection with the rest of the power grid [8], [9]. Although modern wind generators include power electronics converters which have some reactive power regulation capability that allows certain control over voltage disturbances, the capacity of the power electronics is limited [10]. When a contingency occurs in the system, the inability of wind turbines to provide enough reactive

Figure 1.1  Wind resources and load centers in the New England Region [3]
power so that the voltage can go back to its pre-fault value is a major concern. Therefore, dynamic voltage stability, which is defined as the ability of a power system to maintain steady voltages at all buses after a disturbance, is one of the biggest issues regarding wind integration. It should also be pointed out that it is essential to take into account the distinctive features of wind power, such as its usually remote geographical location, when conducting wind integration studies.

Typical wind generation project proposals assume a basic configuration, which just include wind turbines as part of the wind farm. The System Impact Studies (SIS) often identify additional system elements needed to assure that the proposed generation does not degrade the power system performance. These additional system condition installations appear often as significant economic burdens. The present study focuses on analyzing basic wind installations in order to identify the appropriate actions that should be taken to improve their dynamic voltage performance.

1.1.2 Analysis of Existing Literature

As mentioned in Section 1.1.1, dynamic stability is one of the biggest concerns when conducting wind integration studies. Several studies have analyzed it, such as [11], [12], [13] and [14]. However, they are not always focused on dynamic voltage performance, but also on other dynamic magnitudes such as rotor angles. This comes in detriment of a more insightful study of dynamic voltage issues. Some studies like [15] have focused on developing single and aggregated wind turbine models for dynamic simulations, a necessary tool for any wind integration study like the present thesis. Probably the most comprehensive study on dynamic behavior of both inland and offshore wind farms to date is [16]. Mechanical characteristics of wind turbines are taken as a starting point to explain their electrical behavior. However, its focus
is not only on voltage performance, but also on several other dynamic magnitudes such as rotor speed. Furthermore, it does not study the effect of the transmission line connecting wind farms to the rest of the system.

Therefore, there is still a need for studies focusing on dynamic voltage behavior of inland wind farms, which are still by far the mainstream in wind power, while taking into consideration the long transmission lines that typically connect them to the rest of the power grid.

For the present thesis, two kinds of wind turbines have been considered: wind turbines type III and type IV, as they are the dominant types in the market. Type III wind turbines are the most widely used nowadays, and several studies such as [11], [12], [13], [14] have analyzed their dynamic voltage performance using different approaches. However, type IV wind turbines are expected to increase their market share due to their several advantages and sustained cost reduction, and might eventually become the leading type of wind turbine. In spite of these advantages, few studies have been conducted about this turbine technology and its effects on the grid are not widely known [17]. Reference [18] compared the performance of both these kinds of turbines, focusing on rotor speed issues. Literature is scarce regarding dynamic voltage stability studies considering wind IV turbines, as available studies focus on developing control strategies as in [19], [20], [21]. The present thesis will analyze both wind turbine types, with the aim of shedding some light on the impact of type IV wind turbines.

As mentioned in Section 1.1.1, most wind farms are in remote locations and connected through long transmission lines to the rest of the network, which places them in a weak point of the system. Therefore, it is important to analyze the impact that the interconnection between the wind farm and the rest of the grid has on the system’s dynamic performance, and some
studies have dealt with this issue. References [22], [22], [23], [24], [24] consider this matter and analyze, among many other issues such as power-swing stability, the implications of several control schemes for improving wind farm’s voltage performance when connected to the grid through a weak link. Other studies such as [25] share the practical experience of transmission planners dealing with the issue of connecting wind farms to a real power system.

Instead of studying the impact of wind turbines, so that the appropriate actions to remediate the problems can be identified, these studies focus on developing control methods to improve its performance. However, there might be alternative solutions to the problem of poor dynamic voltage performance of basic wind installations, which may be simpler and/or most cost-effective. In addition, most of this research work only considers induction-generator-based wind turbines, leaving out type IV wind turbines.

Many of these studies use the Short Circuit Ratio, a magnitude related to the Thevenin impedance equivalent of the grid, as a measure of the strength of the interconnection. The use of the Thevenin impedance as such to characterize the severity of a fault from a dynamic voltage point of view, which is presented in Chapter 4 of this thesis, is novel. The concept of Thevenin impedance has been used in wind studies to conduct short-circuit analysis in works such as [26], [27], but not in dynamic voltage studies.

As a conclusion for this literature review, it should be pointed out that there is a need for research focusing on dynamic voltage behavior of inland wind farms, while taking into consideration the long transmission lines that connect them to the rest of the power grid. Furthermore, type IV wind turbines need to be further studied, given their projected increase in market share and the very scarce literature currently available.
1.2 Research Objective

The aim of the present thesis is to analyze voltage characteristics of an electric grid connected to wind generation and subject to fault conditions. Given the continuous increase of wind power in the world, the need for studies such as this one becomes critical in order to maintain power quality and stability.

Both type III and type IV wind turbines are to be studied, with the goal of expanding the current knowledge of type III performance and throwing some light on the impact of type IV wind turbines. The ultimate objective of conducting such a study is to be able to identify appropriate actions than can remedi ate the voltage problems caused by wind generation.

While this is an academic study, its practical application has always been on the spotlight of the researchers. The typically remote location of wind resources, particularly in the New England region, makes it necessary to use long transmissions lines to connect wind farms to the rest of the power system. That is why studying the effects of such an electrical connection on voltage performance is one of the cornerstones of this work.

1.3 Research Approach

In order to achieve the goal of quantifying the impact of wind power on dynamic voltage performance of a power grid, several simulations have been conducted. The IEEE standard 39-bus system, which is a simplified representation of the New England electric grid, has been used as a platform to show the result of the study. The software used to conduct the simulations is the Power System Analysis Toolbox (PSAT) for MATLAB, a research-oriented software which gives the user great flexibility and the ability of easy prototyping when compared to commercial tools.
First of all, the performance of synchronous machines and wind turbines type III and IV has been compared. Simulations have been conducted considering synchronous machines and wind turbines subject to the same faults, in order to quantify how the inclusion of a certain kind of wind turbine affects dynamic voltage profiles. In addition, several wind penetration scenarios have been analyzed, which show the impact of a higher wind generation share.

In order to study the impact of a long transmission line connecting the wind farm to the system, several cases of increasing line length have been considered. These cases have been simulated under different fault conditions in the system. The Thevenin impedance seen by the wind bus has been used as a measure of the strength of the point of interconnection, and its relation with several variables that characterize the effects of a fault has been determined.

1.4 Thesis Organization

The organization of the remaining Chapters of this thesis can be summarized as follows:

Chapter 2 discusses the models of the different power system’s elements and devices used in this study, such as synchronous generators, wind turbines and transmission lines. An explanation of the automated simulation process and analysis of results that has been developed for this thesis is also included in this Chapter.

Chapter 3 deals with the different performance of wind turbines and synchronous generators regarding system voltages. Several wind integration scenarios are considered in order to quantify the impact of increasing wind power in the network.

In Chapter 4, the impact that the interconnection of a wind farm has on the system’s dynamic voltage performance is analyzed. The Thevenin impedance seen by the wind bus has been used as a measure of the strength of the point of interconnection, and its relation with several variables that characterize the effects of a fault has been determined.
This thesis concludes with Chapter 5, which includes the conclusions extracted from the thesis’s results and the related topics that should be further investigated in future research studies.
CHAPTER 2
POWER SYSTEM MODELING AND SIMULATION

This Chapter discusses the models of the different power system’s elements and devices used in this study, such as synchronous generators, wind turbines and transmission lines. An explanation of the automated simulation process and analysis of results that has been developed for this thesis is also included at the end of this Chapter.

2.1 Simulation Tool: Power System Analysis Toolbox

The software used to conduct the simulations is the Power System Analysis Toolbox (PSAT) for MATLAB. PSAT is an open-source, freeware, power system analysis toolbox that can be used for power system analysis and control learning, education and research. It is a research-oriented software which gives the user more flexibility and the ability of easy prototyping when compared to commercial tools, which are focused on achieving computational efficiency.

In addition, PSAT has been used for several wind integration studies such as [28], [29], [30], [31]. One of the reasons for its use in wind power analysis is the wind turbine models that PSAT includes, which are based on the models developed in [32], particularly created for conducting dynamic analysis. Furthermore, the wind turbine models implemented in PSAT are adequate for representing a single machine as well as a wind park composed of several generators.

On the other hand, PSAT has some limitations. As mentioned before, it strengthens flexibility for the user in detriment of computational efficiency, which makes it unsuitable for studying real power systems containing thousands of buses. However, this thesis is an academic work which uses IEEE 39-bus system instead of a real power grid as the platform to conduct the
study. The 39-bus test case has been chosen due to its numerous advantages when used for research work, which will be discussed in Section 2.2. Therefore, PSAT is a perfectly valid simulation package for the present work.

As most power system simulation packages, PSAT uses the single phase equivalent representation of a power system. This is an acceptable representation when three-phase balanced magnitudes are considered all over the power system, as it is assumed in this thesis.

In the following Sections, the models of the devices of interest for the present study are going to be discussed. For a detailed description of the rest of the models of power system’s elements included in PSAT, please refer to [32]. A brief description of the physical fundamentals of each of the devices is also included in the following Sections.

### 2.1.1 Synchronous Generator Model

Large-scale power is mainly generated by three-phase synchronous generators, which are the traditional type of generators, driven by steam, hydro or gas turbines in all the conventional power generation facilities before the rise of renewables. The synchronous generator has two main components: the stator and the rotor. The stator contains the armature windings, which are designed to generate balanced three-phase voltages. The rotor contains the field windings, and its function is to induce voltages in the stator’s winding by means of a rotating magnetic field. In order for this magnetic field to be created, a DC excitation system is used to inject a direct current into the rotor’s windings. Moreover, the rotor constantly rotates because it is connected to the already mentioned steam, hydro or gas turbine, and this rotation makes the magnetic field change over time [33].
The synchronous machine model used in PSAT simulations in this thesis represents an order II synchronous machine, which corresponds to the classic electro-mechanical model, used for deducing the classical swing equations in the literature [34]. This model considers a constant amplitude excitation voltage of the rotor windings.

![Three-phase synchronous generator schematic](image)

**Figure 2.1** Schematic of a three-phase synchronous generator [35]

### 2.1.2 Wind Turbine Type III Model

The dominant type of wind turbine in the world is the doubly-fed induction generator (DFIG), also known as type III wind turbine [36]. The electric generator it contains is composed by a rotor and a stator, just like the synchronous machine. The stator is directly connected to the grid via a transformer, while the rotor windings are also connected to the grid via slip rings, an AC to AC power electronic converter and a transformer. The power electronic converter allows the DFIG to supply energy to the grid at the required 60 Hz frequency, regardless of the rotor speed, which is determined by the speed of the wind. With this configuration the energy is delivered to the grid from both the stator and the rotor, hence the term “doubly-fed” [37].
As can be seen in Figure 2.2, the type III wind generator contains a power electronic converter. The dynamic model of the converter in PSAT is highly simplified, as the converter dynamics are assumed to be fast with respect to the electromechanical transients in the system. Therefore, the converter is modeled as an ideal current source represented in the d-q axis frame.

The wind turbine model also contains a voltage controller, which is considered to be part of the converter. This voltage controller modifies the reactive power output of the wind generator by modifying the rotor direct current output of the converter, $i_{dr}$. This rotor direct current is modified by the controller following this differential equation:

$$\frac{d(i_{dr})}{dt} = K_V(v - v_{ref}) - \frac{v}{x_\mu} - i_{dr}$$  

(1)
Where $K_V$ is the controller gain, $v$ is the instantaneous wind bus voltage, $v_{ref}$ is the wind bus reference voltage, typically of 1 pu, and $x_\mu$ is the magnetizing reactance of the wind generator. The only parameter that can be modified by the PSAT user is $K_V$, as the rest of them correspond either to the physical model of the generator, like $x_\mu$, or to the acceptable range of power system bus voltages, like $v_{ref}$.

![Voltage control scheme of a type III wind turbine][32]

The reactive power output $Q$ of the wind turbine is directly dependent on $i_{dr}$. The reactive power injected into the grid by the wind generator PSAT model is given by Eq. (2):

$$ Q = -\frac{x_\mu \cdot v \cdot i_{dr}}{x_s + x_\mu} - \frac{v^2}{x_\mu} \quad (2) $$

Where $x_s$ is the stator reactance.

$Q$ is a magnitude related to the bus voltages in a power system, as deduced in [38]. Therefore, it has been shown through a series of correlated steps that the voltage controller of the wind type III turbine does in fact control the wind bus voltage.
2.1.3 Wind Turbine Type IV Model

The second-most used type of wind turbine in the world is the direct-drive synchronous generator wind turbine (DDSG), also known as type IV. Type IV wind turbine is expected to increase its market share due to its several advantages such as its improved efficiency, suppression of noise, and lower maintenance cost than DFIG [17].

The type IV wind turbine has basically the same structure as the synchronous machine. However, there is one fundamental difference: the rotor of a synchronous generator can rotate at a chosen speed, as its rotational speed is controlled by the input of the steam, hydro or gas turbine connected to it. On the other hand, due to the stochastic nature of wind, the rotor of a type IV wind turbine cannot rotate at a fixed speed without a significant loss of efficiency. Therefore, the AC energy generated by the type IV wind turbine, whose frequency changes with the variability of wind, must be converted into 60 Hz AC energy suitable for being transmitted in a North American power system. Then, the AC output of the wind generator is first rectified into DC and then inverted back to AC at standard 60 Hz grid frequency. The AC-AC conversion is achieved by means of a power electronics device, which decouples the wind turbine from the grid [37].

Figure 2.4 Schematic of a type IV wind turbine [32]
As can be seen in Figure 2.4, the wind generator type IV also contains a power electronic converter. The converter dynamics are assumed to be fast with respect to the electromechanical transients in the system, as they are for the wind generator type III, which highly simplifies the type IV converter model in PSAT. Therefore, the converter is modeled as an ideal current source represented in the d-q axis frame.

The wind turbine model also contains a voltage controller, which is considered to be part of the converter. This voltage controller modifies the reactive power output of the wind generator by modifying the converter direct current output, \( i_{dc} \). This direct current output is modified by the controller following this differential equation:

\[
\frac{d(i_{dc})}{dt} = \frac{K_V(v_{ref} - v) - i_{dc}}{T_V} \tag{3}
\]

Where \( K_V \) is the controller gain, \( v_{ref} \) is the reference bus voltage, \( v \) is the instantaneous wind bus voltage and \( T_V \) is the voltage controller time constant. The parameters that can be modified by the PSAT user are \( K_V \) and \( T_V \).

![Voltage control scheme of a type IV wind turbine](image)

Figure 2.5  Voltage control scheme of a type IV wind turbine [32]
The reactive power output $Q$ of the wind turbine is directly dependent on $i_{dc}$. The PSAT wind turbine type IV model includes, as most turbines of this kind, a permanent magnet rotor (PMG), which means that the power factor of the generator is equal to 1. Therefore, the reactive power output of the stator is 0, and all the reactive power injected to the grid is controlled by the power electronics converter. Then, the $Q$ output of the generator becomes:

$$Q = i_{dc} \frac{v}{\cos \theta} + P \tan \theta$$

(4)

Where $\theta$ is the phase angle of the wind bus voltage and $P$ is the active power output of the type IV wind generator.

As mention in Section 2.1.3, $Q$ is a magnitude related to the bus voltages in a power system. Therefore, it has been shown through a series of correlated steps that the voltage controller of the type IV wind turbine does in fact control the wind bus voltage.

2.1.4 Transmission Line Model

It is convenient to represent a balanced three-phase transmission line by the two-port network shown in Figure 2.6, where $V_S$ and $I_S$ is the sending-end voltage and current and $V_R$ and $I_R$ are the receiving-end voltage and current [39]. This lumped equivalent model of a transmission line, also called the $\pi$-nominal circuit due to its shape similarity with the Greek letter, is an acceptable representation for most studies, and it is the model implemented in PSAT. The magnitudes $Z$ and $Y$ are usually calculated by multiplying the line per-length impedance $z$ and per-length admittance $y$ by the total line length, respectively. A correction factor should be applied to $Z$ and $Y$ when considering long transmission lines, a matter that is discussed in Section 4.1.
2.2 IEEE 39-Bus Test Case

The platform used to conduct this study is the IEEE standard 39-bus system, which represents a greatly reduced model of the New England electric grid. The 39-bus system is a standard system for testing new methods, which has been used by numerous researchers to study both static and dynamic problems in power systems. Using test systems is considered more convenient than using models of real power systems, as the latter are not fully documented and tend to be very big, which makes it difficult to distinguish general trends. Furthermore, the results obtained with models of real systems are less generic than those obtained with test systems [15].

The IEEE 39-bus system has 10 generators, 19 loads, 36 transmission lines and 12 transformers, as can be seen in Figure 2.7.
2.3 Automated Simulation and Analysis

The impact of wind power on dynamic voltage performance of the IEEE 39-bus system is studied in this thesis through time-domain simulations in PSAT. Time-domain simulations are widely used to study the behavior of power systems under contingencies. This kind of simulations includes dynamic models of the power system’s elements and devices, which are described by differential equations. The differential equations are solved by computer simulations packages using numerical methods, which use different techniques in order to improve the efficiency of the simulation while converging to an acceptable solution for the dynamics of the system.
Throughout the work leading to the completion of this thesis, several MATLAB scripts have been developed in order to automatize both the time-domain simulations and the analysis of their results. These scripts perform several tasks which include placing three-phase to ground faults in all buses of the system and running time-domain simulations for each case, while recording some magnitudes of interest to this study such as dynamic bus voltages.

Once these magnitudes are recorded, the developed MATLAB scripts also perform an analysis of the simulation results, saving the PSAT user time from tedious manual calculations. The developed code calculates voltage peaks and sags and recovery times, as shown in Figure 2.8, and runs a statistical analysis of the overall results. In this particular example shown in Figure 2.8 a voltage overshoot can be observed, but the scripts also consider cases in which there are voltage oscillations until returning back to pre-fault values, and properly calculate the recovery time in each case.
One of the techniques used in this thesis to improve the time efficiency of time-domain simulations in PSAT is the adaptive time step. This technique, which is utilized in other disciplines such as Neural Network training algorithms, makes use of a longer time step when the change in the magnitude of system variables is small, but reduces the time step when an event happens in the system, in order to increase the accuracy of the simulation. In the time-domain simulations conducted in PSAT, big time steps are used in the pre-fault and far post-fault time frame, while small time steps are used while the fault is happening or it has been recently cleared. A graphical explanation of the adaptive time step can be found in Figure 2.9, where an $n$-samples-long fault is considered. The code developed in the present thesis to automatize the analysis of the time-domain simulations takes into account the fact that a dynamic sampling rate is used throughout the simulation, which is adjusted by the adaptive time step algorithm.
One of the contributions of this thesis is in fact the code developed for automating the simulations and the analysis of its results, as it will be available to future students conducting power system analysis with PSAT. This code could potentially be included in the PSAT library as an additional functionality of the toolbox, so that all its users can benefit from it, therefore contributing to the philosophy of open-source freeware as PSAT.
CHAPTER 3

COMPARISON OF WIND TURBINES AND SYNCHRONOUS GENERATORS’ PERFORMANCE

A comparison of the dynamic voltage performance of synchronous machines and basic wind installations under fault conditions in the system is presented in this Chapter. Both wind turbines type III and type IV are to be studied, with the goal of expanding the current knowledge of type III performance and shedding some light on the impact of type IV wind turbines. In addition, several wind integration scenarios are considered in order to quantify the impact of increasing wind power in the network.

3.1 Low-Wind-Penetration Scenario

In the first place, a general analysis of the voltage performance of wind farms under contingencies in the system will be presented. This performance has been compared with that of synchronous machines subject to the same faults. The same simulations have been conducted using both synchronous machines and wind farms, in order to quantify how the inclusion of wind generation affects dynamic voltage profiles.

The IEEE 39-bus test case power system was used as the case study to show the developed methodology. The original 39-bus system, from now on referred to as the original case, contains ten synchronous machines as sources of electric power. The effects of wind penetration in this system have been studied by connecting some wind farms to it, while the total amount of generation in the system has been kept constant. Thus, when including a certain amount of wind generation, the amount of power generated by synchronous machines has been reduced accordingly.
For this study, two kinds of wind farms have been considered: type III and type IV, due to several factors discussed in previous Chapters. The PSAT wind turbine models used for the simulations, which are discussed in Chapter 2, are adequate for representing a wind farm composed of several generators, and they were used as such in all the simulations in this thesis. This aggregate model of a wind generator includes the differential equations corresponding to the dynamic model of just one turbine, because modelling each of the hundreds of turbines that constitute a wind farm would make the simulations tremendously inefficient. However, the model makes certain calculations in order to take into account the contribution of all the wind turbines in the farm while maintaining the efficiency of the simulations, as discussed in [15].

Every wind farm used was composed of 500 units with a power rating of 2 MVA each, in order to make them equivalent to each of the synchronous generators in the original case. The inertia of the wind farm was set to be equal to the inertia of the synchronous machines, as well as its voltage level. It is important to point out that synchronous generators typically have a higher inertia than wind turbines. However, this study focuses on the inherent voltage characteristics of wind turbines and synchronous generators so, in order to compare them in a one-to-one basis, the inertia, which is related to phase-angle stability rather than voltage stability, was set equal. The rest of the parameters of the wind farm were set to its default values in PSAT. The wind speed profile was assumed to be constant over time in all simulations, which is a realistic assumption given that the time interval considered in all simulations is just a few seconds long.

The voltage controllers of the wind turbines will play a significant role in the dynamic voltage performance of the system. The parameters of the voltage controllers of both wind type III and type IV wind turbines were set to equal values, in order to compare both types of turbines on a one-to-one basis. The voltage control gain of both types of turbines, $K_V$, was set to
the default value of 10, while the time constant of the type IV controller, \( T_V \), was set to 1 second in order to make it equivalent to the type III controller, which has a fixed time constant of 1 second. More details about the voltage controllers of both wind turbine models can be found in Sections 2.1.2 and 2.1.3.

Instead of studying the different voltage performance when modifying the controller parameters, this study focuses analyzing the impact of wind turbines, so that the appropriate actions to remediate the problems can be identified. Much of the literature analyzed in Section 1.1.2 deals with developing several control schemes to improve wind turbines’ performance. However, there might be alternative solutions that may have advantages over this strategy. In addition, the vast majority of the solutions offered by these studies propose the refinement of the turbine voltage controller gains on a case-to-case basis, which have therefore limited positive effect as they are not universal, as pointed out by [24].

### 3.1.1 Measurement of the Strength of the System

In this Section, the strength of the system in a low-wind-penetration scenario is going to be measured. The strength is defined in this case as how severe of a contingency the system can withstand in terms of fault duration, regardless of the fault location. The system withstands a fault when all the bus voltages are able to return to its pre-fault value.

Using the original case, which includes ten synchronous machines, a three-phase-to-ground fault was simulated in every bus of the system, one bus at a time. The duration of the fault was increased in 0.1-second intervals until any bus in the system became unstable due to an angular loss of synchronism of the system’s generators. This occurred for a 0.4-second-long fault, for which three fault locations made the system unstable. These fault locations that lead the system to instability were bus 29, a load bus, and buses 37 and 38, generator buses.
The same simulations were conducted again, but considering two low-wind-penetration scenarios instead of the original case. These two scenarios were created by replacing the synchronous generator in bus 37 by a wind farm of type III and type IV, which correspond to a 10% of wind penetration. As mentioned before, the inertia, voltage level and generating capacity of the wind farms were equal to those of the synchronous generator they replaced.

Again, 0.4-second-long, three-phase-to-ground faults were applied to every bus in the system. It is important to point out that no lines were opened so that the post-fault system topology remained unchanged. The simulation results in both cases were the same as in the synchronous machine case: faults located in buses 29, 37 and 38 lead the system to instability. This concludes that the 10% wind penetration scenario does not deteriorate the system’s post-fault, steady-state voltage stability.

3.1.2 Impact of Wind Integration on Dynamic Voltage Performance

However, the impact that the inclusion of wind generation has on dynamic voltage performance must also be considered. Post-fault voltage peaks could be observed in some buses for each of the simulations. An example of this behavior can be seen in Figure 3.1. A statistical analysis of the overvoltage peaks for all fault locations considering a fixed fault duration of 0.25 seconds was made, and has been included in Table 3.1. The duration of the fault corresponds to the backup clearing time for protection relays in some power systems. The same analysis was made for the longest voltage recovery time, defined as the longest time for a bus voltage in the system to go back to ±1% of its pre-fault voltage value, also shown in Table 3.1.
Figure 3.1  Voltage profiles of four of the system buses for a fault located in bus 4

Table 3.1  Statistical analysis of the dynamic voltage performance of synchronous and wind generators

<table>
<thead>
<tr>
<th></th>
<th>Overvoltage peak</th>
<th>Recovery time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Synchronous machine</strong></td>
<td>Mean: 1.067 pu</td>
<td>Mean: 1.20 sec</td>
</tr>
<tr>
<td></td>
<td>Std deviation: 0.004 pu</td>
<td>Std deviation: 0.63 sec</td>
</tr>
<tr>
<td><strong>Wind type III</strong></td>
<td>Mean: 1.071 pu</td>
<td>Mean: 1.38 sec</td>
</tr>
<tr>
<td></td>
<td>Std deviation: 0.008 pu</td>
<td>Std deviation: 0.55 sec</td>
</tr>
<tr>
<td><strong>Wind type IV</strong></td>
<td>Mean: 1.116 pu</td>
<td>Mean: 3.79 sec</td>
</tr>
<tr>
<td></td>
<td>Std deviation: 0.030 pu</td>
<td>Std deviation: 1.90 sec</td>
</tr>
</tbody>
</table>
Section 3.1.1 shows that the steady-state voltage stability of the system is not deteriorated due to the addition of wind, so one can conclude that the dynamic performance deterioration in this low-wind-penetration case is due to the wind controllers’ action, and not to a lack of reactive power capability of the wind turbines. Therefore, tuning the wind voltage controller parameters seems to be the most sensible approach in this case, in order to improve the dynamic voltage performance of the system.

It is also important to realize that the type IV wind turbines show a worse dynamic performance than type III. Type IV wind turbines are thought to behave better in terms of voltage stability than wind type III, due to the bigger power electronics converter they possess, which provides them with higher reactive power capability. However, the lack of reactive power is not an issue for either of the wind turbine types in this case, as show the results in Section 3.1.1. Therefore, the different voltage control scheme of the PSAT type III and type IV models should be further investigated, as it is the cause of the worse performance shown by type IV. Although the control parameters of both turbine types were set to the same values, the voltage control schemes of type III and IV are partially different, as discussed in Sections 2.1.2 and 2.1.3.

It should also be studied to what extent this control schemes can be modified, as they do not only depend on the structure of the voltage controller, but also on the $Q$ output of the machines. That is because the $Q$ output of type III and IV wind turbines, described by Eq. (2) and Eq. (4), respectively, is partially determined by the inherent physical characteristics of each type of turbine.

As can be seen in Figure 3.2, tuning the controller gain does in fact change the voltage response of the wind bus. The left-hand plot represents the voltage performance of the wind bus when using the default gain of the wind turbine voltage controller, while the right-hand plot
shows the behavior of an adjusted gain for that particular fault. However, the present thesis did not focus on adjusting the controller gains because, as pointed out by [24], these adjustments are performed on a case-to-case basis. In addition, wind turbines developed by different manufacturers might have different controller schemes, so a study dealing with modifying generic controller gains would have rather limited practical usefulness. The real wind turbine models developed by different manufacturers are proprietary, and are usually provided to power system planners as a “black box” model. However, many efforts have been put to develop generic models as the ones used in PSAT [15]. While the dynamic model of different brand wind turbines can be well represented by a generic model, as all of them are based on the same working principles, the tuning of a generic controller model cannot be exported to a different controller, as it is highly dependent on the particular controller scheme.

![Figure 3.2 Effect of tuning the wind turbine controller on voltage performance](image)

Figure 3.2 Effect of tuning the wind turbine controller on voltage performance
3.2 Increasing Wind Penetration

Once the dynamic voltage deterioration due to a 10% wind penetration was shown, as presented in Section 3.1.2, several cases of wind penetration were considered. The objective was to compare the effects that a three-phase fault has on an increasing wind penetration scenario. Seven cases were considered: the original 39-bus system including its ten synchronous machines; 10% penetration of wind type III; 20% penetration of wind type III; 30% penetration of wind type III; 40% penetration of wind type III; 10% penetration of wind type IV; and 20% penetration of wind type IV. The wind farms were progressively added to buses 37, 30, 38 and 39 to reach the 40% penetration scenario. For this study, a three-phase-to-ground, 0.25-second-long fault located in bus 17 was considered. As a starting point for this wind integration study, bus 17 was chosen due to its middle distance from the wind farm buses in the 39-bus test case.

The results of these simulations have been summarized in Table 3.2 and Table 3.3. For each of the seven cases, the best and worst voltage performance was recorded. An example of the transient voltage profiles in bus 30 obtained for the different cases can be seen in Figure 3.3.
Figure 3.3  Voltage profiles in bus 30 for several wind penetration scenarios

Table 3.2  Best and worst wind penetration scenarios for post-fault overvoltage

<table>
<thead>
<tr>
<th></th>
<th>Highest</th>
<th>Lowest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 30</td>
<td>Wind IV 20%</td>
<td>Synchronous</td>
</tr>
<tr>
<td>Bus 37</td>
<td>Wind IV 20%</td>
<td>Synchronous</td>
</tr>
<tr>
<td>Bus 38</td>
<td>Wind III 40%</td>
<td>Synchronous &amp; Wind III 10%</td>
</tr>
<tr>
<td>Bus 39</td>
<td>Wind III 40%</td>
<td>Synchronous</td>
</tr>
</tbody>
</table>

Table 3.3  Best and worst wind penetration scenarios for voltage recovery time

<table>
<thead>
<tr>
<th></th>
<th>Longest</th>
<th>Shortest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 30</td>
<td>Wind IV 20%</td>
<td>Synchronous</td>
</tr>
<tr>
<td>Bus 37</td>
<td>Wind IV 10%</td>
<td>Synchronous</td>
</tr>
<tr>
<td>Bus 38</td>
<td>Wind III 40%</td>
<td>Synch &amp; Wind III 10%</td>
</tr>
<tr>
<td>Bus 39</td>
<td>Wind IV 10% and 20%</td>
<td>Synchronous</td>
</tr>
</tbody>
</table>
The synchronous generator always shows the best performance, although the type III 10% penetration scenario had very similar voltage profiles in most of the cases. However, the progressive addition of wind deteriorates the dynamic response of the voltages. This result agrees with previous studies which state that for high penetration levels of wind energy in the grid, the impacts to the system become of great concern [6], [8], [9]. In addition, it can be seen that type IV shows a worse performance than type III, even for lower penetration scenarios. This result confirms the conclusions from Section 3.1.2, pointing towards the different voltage control schemes of the type III and type IV turbines as the cause for the worse dynamic performance shown by type IV.
CHAPTER 4

INFLUENCE OF WIND FARM POINT OF INTERCONNECTION

The influence that the point of electrical interconnection between a wind farm and the rest of the power system has on the bus voltages’ performance has been analyzed in this Chapter. As most wind farms are in remote locations where the wind conditions are optimum for obtaining electric energy, they are usually connected through long transmission lines to the rest of the network, which places them in a weak point of the system. That is why studying the effects of such an electrical connection on voltage performance is one of the cornerstones of this work.

In the present study, several interconnection scenarios have been analyzed by using the Thevenin impedance seen by the wind bus, which was used as a measure of the strength of the interconnection. These different interconnection scenarios were created by adding a transmission line between the wind farm’s step-up transformer and the rest of the network, and modifying its model parameters appropriately. The relation between the Thevenin impedance and two variables that characterize the effects of the fault, such as the time interval until the voltage returns to normal conditions and the highest difference between the pre-fault and post-fault voltages is presented.

It is important to point out that previous studies dealing with the issue of weak connections of wind farms used the Short Circuit Ratio as a measure of the strength of the connection. The use of the Thevenin impedance for analyzing the impact of the transmission line on dynamic voltage performance is novel.
For this study, a 10% wind penetration scenario was considered, using both wind turbines type III and type IV. One of the ten synchronous machines in the original 39-bus test case was substituted by a wind farm of the same MVA rating, voltage rating and inertia. This procedure is equivalent to the one used in Section 3.1.1.

4.1 Description of Line Length Increase

The π-nominal model of a transmission line discussed in Section 2.1.4 is used throughout this thesis to represent a transmission line, as in most power system studies. The series impedance $Z$ and shunt admittance $Y$ in Figure 2.6 can be calculated using Eq. (5) and Eq. (6):

$$Z = z l$$  \hspace{1cm} (5)  

$$Y = y l$$  \hspace{1cm} (6)  

Where $l$ is the line length and $z$ and $y$ are the per-length impedance and admittance of the line, given by Eq. (7) and Eq. (8):

$$z = R + j\omega L$$  \hspace{1cm} (7)  

$$y = G + j\omega C$$  \hspace{1cm} (8)  

Where $R, L, G, C$ are the per-length resistance, inductance, conductance and capacitance of the line, respectively. The imaginary unit is symbolized as $j$, while $\omega$ stands for the frequency of the AC energy flowing through the lines, which is of $2\pi60$ rad/s in a North American power system. $G$ is usually neglected in 60-Hz lines, so it is not included in the π-representation of the line. These per-length parameters $R, L$ and $C$ depend on the physical characteristics of the line, such as the type of conductor used, the number of wires per electrical
phase, the spacing between the phases and the addition or omission of a neutral conductor, as explained in [40].

It should be pointed out that the $\pi$-nominal model is just an approximation for the real physical model of a transmission line, as in reality the line parameters are not lumped but distributed along the line. Using classical electromagnetic transmission line theory and assuming that the line parameters are uniformly distributed over the length of the line, the differential equations that accurately describe the mathematical model at any point of the line can be deduced. By solving those differential equations, the most detailed description of a transmission line can be obtained. The explanation can be found on [39].

Nevertheless, the $\pi$-nominal model of the line is acceptable for short and medium length lines, of lengths lower than 250 km. For long transmission lines, a $\pi$-equivalent model can be used, obtained by applying certain correction factors to $Z$ and $Y$ of the $\pi$-nominal model. Those correction factors take into account the solution of the differential equations given by classical electromagnetic transmission line theory, in order to have a more accurate $\pi$-model. Being $Z'$ and $Y'$ the elements of the $\pi$-equivalent model shown in Figure 4.1, their relation with the $Z$ and $Y$ elements of the $\pi$-nominal model is given by Eq. (9) and Eq. (10).

![Figure 4.1 $\pi$-equivalent circuit of a transmission line](image-url)
\[ Z' = Z \frac{\sinh(\gamma l)}{\gamma l} \]  

(9)

\[ Y' = Y \frac{\tanh(\gamma l)}{\gamma l} \]  

(10)

Where \( \gamma \) is the propagation constant of the line, defined by Eq. (11):

\[ \gamma = \sqrt{\frac{\gamma'}{Z}} \]  

(11)

The hyperbolic sine and hyperbolic tangent functions take a value of approximately 1 when the value of \( l \) is not high, as shown in Figure 4.2. Figure 4.2, where the x-axis range has been fixed to the typical range for lines shorter than 300 km, is the graphical explanation as to why the \( \pi \)-nominal model is valid for short and medium length lines.

![Figure 4.2 Hyperbolic sine and hyperbolic tangent functions for transmission lines](image-url)
For the work developed in this Chapter, the point of interconnection of the wind farm with the rest of the system was modified by adding a power transmission line between the wind farm’s step-up transformer and the rest of the network. This was achieved by adding an extra transmission line located between bus 25 and bus 37 of the IEEE 39-bus system. Therefore, a 40th bus was added to the system, being the wind farm located in bus 37, its step-up transformer between buses 37 and 40, and the extra transmission line between buses 40 and 25. In the base case considering the extra line, the per-unit values of \( Z \) and \( Y \) for its \( \pi \)-model were set equal to the ones corresponding to the line that connects buses 1 and 2 in the 39-bus system, in order to represent a realistic transmission line. Since the per-length magnitudes \( z \) and \( y \) are not available for the 39-bus test case, it is not possible to estimate the real length of the line. Certain utilities in the New England region were consulted for this study regarding the generic per-length values of their line parameters, but they were reluctant to provide this information due to security reasons.

Several cases of the connecting transmission line were considered, each of them obtained by modifying the \( Z \) and \( Y \) values of the \( \pi \)-model in order to represent increasing line lengths. For the sake of simplicity, the \( Z \) and \( Y \) values of the \( \pi \)-model were multiplied by the same constant for each of the cases of extra transmission line considered in this study, in order to obtain \( Z' \) and \( Y' \). For future studies, given that generic per-length parameters of a transmission line can be provided by a utility, Eq. (9) and Eq. (10) can be used to calculate the correction factors for the \( \pi \)-equivalent model.

The phasor diagram in Figure 4.3 represents the different values of the Thevenin impedance seen by the wind farm bus for the several cases of extra transmission line considered, each of which was obtained by modifying the values of the \( \pi \)-model parameters as
mentioned before. These are per-unit values, being the impedance base used in that bus of 4 Ω. The power base in the system was 100 MVA and the voltage base in the wind bus was 20 kV.

4.2 Thevenin Impedance Calculations

The Thevenin impedance is calculated throughout this thesis by using the impedance matrix of the system, $Z_{bus}$, using a procedure detailed in some power system analysis books as [41]. The procedure is summarized in this Section.

Figure 4.4 shows a general power system where $k$ is the bus of interest for calculating the Thevenin equivalent. Initially, let the circuit not be energized so that the bus currents and voltages are zero. Then, a current of $\Delta I_k$ (in amp or per-unit) is injected from bus $k$ into the system through a current source connected to the voltage reference node, causing a $\Delta V$ in every bus of the system.

Figure 4.3 Phasor diagram of the Thevenin impedances seen by the wind farm
The resulting voltage changes at all buses of the network due to the injected current, indicated by the incremental quantities $\Delta V_1$ to $\Delta V_n$, are given by Ohm’s law as shown in Eq. (12):

$$
\begin{bmatrix}
\Delta V_1 \\
\Delta V_2 \\
\vdots \\
\Delta V_k \\
\vdots \\
\Delta V_n
\end{bmatrix} =
\begin{bmatrix}
Z_{11} & Z_{12} & \cdots & Z_{1k} & \cdots & Z_{1n} \\
Z_{21} & Z_{22} & \cdots & Z_{2k} & \cdots & Z_{2n} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
Z_{k1} & Z_{k2} & \cdots & Z_{kk} & \cdots & Z_{kn} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
Z_{n1} & Z_{n2} & \cdots & Z_{nk} & \cdots & Z_{nn}
\end{bmatrix}
\begin{bmatrix}
\Delta I_k \\
0 \\
\vdots \\
0 \\
\vdots \\
0
\end{bmatrix}
$$

(12)

Where the only nonzero entry in the current vector corresponds to row $k$, which contains $\Delta I_k$. Therefore, Eq. (12) equation can be simplified to Eq. (13):

$$
\begin{bmatrix}
\Delta V_1 \\
\Delta V_2 \\
\vdots \\
\Delta V_k \\
\vdots \\
\Delta V_n
\end{bmatrix} =
\begin{bmatrix}
Z_{1k} \\
Z_{2k} \\
\vdots \\
Z_{kk} \\
\vdots \\
Z_{nk}
\end{bmatrix}
\Delta I_k
$$

(13)

Now these voltage changes can be added to the original bus voltages, which can be considered to be nonzero by using the superposition theorem for circuits given by Eq. (14):

$$
V = Z_{bus} \Delta I_{initial} + Z_{bus} \Delta I
$$

(14)
Where $\mathbf{V}$ is the bus voltages vector, $\mathbf{I}_{\text{initial}}$ is the initial injected currents vector and $\Delta \mathbf{I}$ is the vector of injected currents changes.

Therefore, the equation for the voltage at bus $k$ comes up to be:

$$V_k = V_k^{\text{initial}} + Z_{kk} \Delta I_k$$

(15)

The circuit corresponding to Eq. (15) is shown in Figure 4.5, from where it can be deduced that the Thevenin impedance at a particular bus $k$ of the system is given by:

$$Z_{\text{Thev}} = Z_{kk}$$

(16)

![Figure 4.5 Thevenin equivalent circuit at bus $k$](image)

Where $Z_{kk}$ is the diagonal component in row $k$ and column $k$ of the impedance matrix of the system, $\mathbf{Z}_{\text{bus}}$.

The values of the Thevenin impedance seen by the wind bus that are represented in Figure 4.3 were calculated using this procedure.
4.3 Fixed Fault Duration

For each of these cases of transmission line connecting the wind farm shown in 4.3, a three-phase-to-ground, 0.25-second-long fault was applied in every bus of the system, while the wind farm was located in bus 37. The duration of the fault corresponds to the backup clearing time for protection relays in some power systems. Time-domain simulations were conducted, and the voltage performance of every bus in the system was analyzed. After the fault was cleared, peaks in the wind bus and near buses could be observed, similar to the ones in Figure 3.1.

The relation between the Thevenin reactance, $X_{The}$, and the magnitudes that characterize the fault effects is presented from Figure 4.6 through Figure 4.8 for faults located in three of the system buses. These are just three examples out of the forty obtained, as a fault was placed in every bus of the system. Every bus showed a similar behavior to the ones included in these plots, thus Figure 4.6 through Figure 4.8 give the reader a good idea of the general trend. Figure 4.9 includes the mean values for all fault locations in the system.

The upper plot in Figure 4.6 through Figure 4.9 presents the highest difference between the post-fault voltage peak and the pre-fault voltage value of that same bus as a function of $X_{The}$. This highest voltage difference was in every case seen in the wind farm bus. The lower plot in Figure 4.6 through Figure 4.9 shows the longest voltage recovery time for any bus in the system as a function of $X_{The}$, which also corresponds in every case to the recovery time of the wind farm bus. The recovery time is defined in this case as the time it takes the voltage to go back to ±1% of its pre-fault value. A graphical explanation of the voltage overshoot difference and recovery time can be found in Figure 2.8. The results shown from Figure 4.6 through Figure 4.9 correspond to the analysis made using a wind type III wind farm.
Figure 4.6 Overvoltage and recovery time as a function of $X_{Thev}$, for a wind farm type III in bus 37 and a fault in bus 1.

Figure 4.7 Overvoltage and recovery time as a function of $X_{Thev}$, for a wind farm type III in bus 37 and a fault in bus 9.
Figure 4.8  Overvoltage and recovery time as a function of $X_{\text{Thev}}$, for a wind farm type III in bus 37 and a fault in bus 27.

Figure 4.9  Mean overvoltage and recovery time as a function of $X_{\text{Thev}}$, for a wind farm type III.
As can be seen from Figure 4.6 through Figure 4.9, both the overvoltage difference and the recovery time increase as $X_{Thev}$ increases, meaning that the increase in length of the connecting transmission line deteriorates the dynamic voltage performance of the system. The plot shows that there is a correlation between these two magnitudes, which characterize the impact of the fault on the voltage performance of the system, and the Thevenin reactance seen by the wind farm bus. A second order regression has been plotted on top of the data obtained from the simulations, showing it to be a good approximation. These results also show that the interconnection between the wind farm and the rest of the power system plays a significant role on the effects of a fault on the voltage performance of the system buses, as the dynamic voltage deterioration is quite significant with an increasing-length line.

The original 39-bus case, in which no additional line was added to connect the wind farm to the rest of the system, corresponds to the lowest value of $X_{Thev}$ shown in the plots. This case shows the lowest overvoltage and recovery time, as can be seen from Figure 4.6 through Figure 4.9. Therefore, another important conclusion can be made by analyzing the plots: the results of the simulations show that the best option from the voltage performance point of view for integrating a new wind farm to a power grid consists on connecting it directly to the existing electric lines to a low Thevenin impedance system node. However, as this might not always be feasible due to the impossibility of freely choosing the location of a new wind farm, which is subject to weather and environmental constraints, this analysis shows that the electric line used for the interconnection should have as small reactance as possible. This can be achieved by the addition of shunt capacitors at both ends of the transmission line, which would reduce the effective reactance of the line.
All in all, the results show that the Thevenin reactance is a good tool when assessing the impact of a potential fault on the dynamic voltage performance of the wind bus. The value of $X_{\text{Thev}}$ seen by the wind bus can be used, as a first approximation, to predict the severity of a fault in the wind terminal. This is particularly useful when there are several available options for connecting a wind farm to a power system. As compared to the Short Circuit Ratio, the main advantages of the Thevenin impedance are its straight-forward derivation for the impedance matrix and the easiness of conducting circuit calculations by using the Thevening equivalent. This equivalent circuit can provide a simple theoretical explanation to the causes of voltage deterioration in each case.

The dynamic voltage performance observed in Chapter 3, and Figure 4.6 through Figure 4.9, raises a question about overvoltage regulations in power systems. Institutions such as the North American Electric Reliability Corporation (NERC) have thoroughly studied low-voltage-ride-through characteristics of wind turbines, and developed standards that utilities must follow to maintain stability in their systems. However, high-voltage regulation has not been paid much attention to. The present work shows that there is a need for a deeper knowledge of power system overvoltages, and agencies like NERC should consider developing standards that regulate them in order to ensure power quality in North America.

The plots from Figure 4.6 through Figure 4.8 show another interesting fact: both the overvoltage and recovery time of the wind bus can be fairly well approximated by a 2nd order polynomial, as mentioned before. In order to check the goodness of the polynomial fit for a fault in any bus of the system, the R-squared of the simulation samples with respect to the polynomial fit was calculated. The R-squared, or $R^2$, is a number between 0 and 1 that indicates how well a statistical model fits a set of data. An $R^2$ of 1 indicates that the model perfectly fits
the data, while an $R^2$ of 0 indicates that the model does not fit the data at all. $R^2$ is defined by the following equation:

$$R^2 = 1 - \frac{RSS}{TSS}$$  \hspace{1cm} (17)

$TSS$ is the total sum of squares, defined as the sum over all data samples of the squared differences of each sample from the overall mean:

$$TSS = \sum_i (y_i - \bar{y})^2$$  \hspace{1cm} (18)

Where $y_i$ are the data samples and $\bar{y}$ is their mean.

$RSS$ is the residual sum of squares, defined as the sum of the squares of residuals, which are the deviation of the values predicted by the model from the actual empirical values of the data:

$$RSS = \sum_i e_i^2 = \sum_i (y_i - f_i)^2$$  \hspace{1cm} (19)

Where $e_i$ are the residuals and $f_i$ are the values predicted by the model.

The R-Squared of the simulation data with respect to the 2$^{nd}$ order polynomial fit was calculated for every fault location. The results can be seen in Figure 4.10 and Figure 4.11.
Figure 4.10  R-squared for the overvoltages as a function of $X_{ThEv}$, for a wind farm type III

Figure 4.11  R-squared for the recovery time as a function of $X_{ThEv}$, for a wind farm type III
These plots show that the accuracy of the fit is over 95% for most buses except for bus 25 for the overvoltage regression and bus 37 for the recovery time regression, both having a significantly poorer accuracy. Bus 37 corresponds to the wind farm bus, and bus 25 is the bus that connects the extra transmission line to the rest of the system. The likely reason for these buses not following the 2nd order trend that other buses do is their proximity to the wind controller, which has a much more significant control capability when the fault is located near it. However, when the fault is further from the wind bus, the wind controller does not have such a significant influence, and the dynamics of the whole system play an important role too.

The high accuracy of the 2nd order regression for every bus in the system located within a certain distance of the wind bus is interesting for several reasons. On the one hand, a parabola is a very convenient description for conducting mathematical manipulations, so having such relationship between the magnitude that characterizes a transmission line and the magnitudes that characterize the effect of a fault can open new theoretical studies on the matter. Furthermore, it is surprising to realize that such a complex system as a power grid, which is overall a very convoluted physical model due to all the dynamics of the different devices it is composed of, can be represented by a mathematical expression as simple as a 2nd order polynomial. The theory behind this parabola correlation could be considered as a topic for future studies.

The relation between the Thevenin reactance, $X_{Thev}$, and the magnitudes that characterize the impact of a fault was also determined for a type IV wind farm. Figure 4.12 through Figure 4.14 present this relation for three of the system buses.
Figure 4.12  Overvoltage and recovery time as a function of $X_{Thev}$, for a wind farm type IV in bus 37 and a fault in bus 5.

Figure 4.13  Overvoltage and recovery time as a function of $X_{Thev}$, for a wind farm type IV in bus 37 and a fault in bus 15.
Figure 4.14  Overvoltage and recovery time as a function of $X_{Thev}$, for a wind farm type IV in bus 37 and a fault in bus 28

Only four samples of the Thevenin reactance can be seen in these plots, when compared to the six samples shown in the corresponding type III plots. The two highest values of $X_{Thev}$ are not included in the plots due to singularity issues that arose when conducting time-domain simulations using the type IV wind turbine model. For the fault located in certain buses, the Jacobian of the state matrix of the system, which is computed during the time-domain simulation in order to solve for the values of the state variables in each time step, became singular. This issue could be solved by increasing the fault impedance, but doing so was inaccurate for this study since only three-phase-to-ground faults are considered. Therefore, if the faulted bus voltage does not reach a value close to 0 per-unit due to an excessively high fault impedance, the simulation cannot be considered valid for this analysis. The singularity issues were particularly significant for the two highest values of $X_{Thev}$, for which several buses
in the system incurred in singularities, and therefore those values of $X_{Thev}$ had to be left out of the study.

The R-squared analysis for the 2\textsuperscript{nd} order polynomial fit of all the system buses when considering a type IV wind turbine is presented in Figure 4.15 and Figure 4.16. The missing samples in the plots correspond to buses which incurred in singularities.

![Figure 4.15](image.png)  

**Figure 4.15**  R-squared for the overvoltages as a function of $X_{Thev}$, for a wind farm type IV
Although the accuracy of the 2\textsuperscript{nd} order regression is also very high, the result is not as significant as for type III, since in this case some buses and some values of $X_{Thev}$ had to be left out of the analysis.

Due to the disappointing simulation performance of the PSAT type IV model, a literature review was conducted, in search of studies mentioning similar issues. Some, such as [42], have pointed out discrepancies seen in the results from different transient stability software packages, which may give substantially different results for very similar system models. Reference [42] deals with developing validation methodologies for different simulation packages. In addition, other studies have proposed the use of alternative dynamic models for systems with weak grids, since they consider that certain simplifications in the model should not be made for these cases [24], [43]. As wind integration studies usually fall under this category of weak systems, due to the long transmission lines typically needed to connect the wind farm to
the rest of the network, the dynamic models developed in studies such as the ones cited should be getting more attention.

Therefore, this study concludes that further investigation regarding the dynamic model of type IV wind turbines is needed, and should particularly be brought to the attention of PSAT developers.

4.4 Increasing Fault Duration

For concluding the study about the influence of the wind farm point of interconnection, the impact of the fault duration was analyzed. The same six cases of connecting transmission line as in the previous Sections were considered, as shown in the phasor diagram in Figure 4.3, and for each of them a fault was placed in three of the system buses and its duration was sequentially increased. The three fault locations selected were bus 11, a bus far from the wind farm; bus 17, a bus within middle distance of the wind farm; and bus 26, a bus close to the wind farm. The results can be observed from Figure 4.17 through Figure 4.19, all of which consider a type III wind farm. This study was not conducted for a type IV wind farm due to the singularity issues encountered in Section 4.3.

Figure 4.17 through Figure 4.19 present the magnitudes that characterize the severity of the fault, both the voltage overshoot and the recovery time, as a function of the fault duration. The several cases of connecting line length are represented using different colors for the curves. The legend entries for each of the curves, Z1 to Z6, represent increasing length of the connecting transmission line, where Z1 corresponds to the original case with no extra line and Z6 corresponds to the longest line considered. The increasing values of Z also correspond to increasing values of $X_{Thev}$ because, as explained in previous Sections, $X_{Thev}$ increases with line length.
Figure 4.17  Overvoltage and recovery time as a function of fault duration, for a wind farm type III in bus 37 and a fault in bus 11

Figure 4.18  Overvoltage and recovery time as a function of fault duration, for a wind farm type III in bus 37 and a fault in bus 17
These plots show that the combined effect of an increasing value of $X_{Thav}$ and increasing fault duration can have severe effects on the dynamic voltage performance of the system. One important conclusion can be made from these results: the clearing time of a fault is particularly important for cases in which a long transmission line is used to connect the wind farm to the system. Therefore, utilities would have to make a higher investment in fast-actuating protection relays for their grid in case they have a weak wind farm connection. An analysis of the best option from an economical point of view should be made by the utility in such a case, as it might be less expensive to invest in improving the transmission grid rather than in state-of-the-art protection relays.
CHAPTER 5

CONCLUSIONS AND FUTURE WORK

In the present thesis, the IEEE 39-bus test case has been used to develop a methodology to study dynamic voltage characteristics of a power system with wind penetration. This work has set the base for extending the analysis to the real New England power system.

One of the contributions of this thesis is the code developed for automating the simulations and the analysis of its results, as it will be available to future students conducting power system analysis with PSAT. This code could potentially be included in the PSAT library as an additional functionality of the toolbox, so that all its users can benefit from it, therefore contributing to the philosophy of open-source freeware as PSAT.

The dynamic voltage performance observed in Chapters 3 and 4 raises a question about overvoltage regulations in power systems. Institutions such as NERC have thoroughly studied low-voltage-ride-through characteristics of wind turbines, and developed standards that utilities must follow to maintain stability in their systems. However, high-voltage regulation has not been paid much attention to. This thesis shows that there is a need for a deeper knowledge of power system overvoltages. It is important to mention that the voltage overshoot following the fault clearing is directly linked with the voltage regulators of the generators, and this work considered a constant excitation for the synchronous machines. As future work to expand the study presented in this thesis, a more detailed model of the voltage regulators can be considered. This future study will show if the overshoots are a still a concern, and if they should be brought to the attention of regulation agencies as NERC.
One of the goals of this thesis was to shed some light on the not very well studied type IV wind turbines. The singularity issues encountered when conducting time-domain simulations using this type of wind turbine show that further study is needed regarding its modelling, and particularly the PSAT model for it should be further validated.

The analysis of the simulations conducted in Chapter 4 shows that the interconnection between the wind farm and the rest of the power system plays a significant role on the effects of a fault on its voltage performance. The Thevenin reactance seen by the wind bus, a concept not explicitly used before in dynamic voltage studies, has been proved to be a good tool when assessing the impact of a fault on the system. The Thevenin reactance is particularly useful when there are several available options for connecting a wind farm to a power system. In addition, it was shown that a 2nd order polynomial can represent with a high level of accuracy the relation between the magnitudes that characterize the severity of the fault and the Thevenin reactance seen by the wind bus, for every bus in the system located within a certain distance of the wind bus.

Chapter 4 has also shown that the combined effect of a long transmission line connecting the wind farm to the system and increasing fault duration can have severe effects on the dynamic voltage performance of the network. Therefore, an analysis of the best option from an economical point of view should be made on a case-to-case basis between improving the electrical connection of the wind farm and installing fast-actuating protection relays.

Regarding future work, the main goal should be to extend the present study to the real New England power grid. As a first step, a study using a more detailed modeling of synchronous machines which includes automatic voltage regulators should be conducted. For this work, it is
recommended to make use of a bigger test case than the 39-bus system, as it would allow analyzing the behavior of wind farms in a bigger power system.

In addition, the different voltage control scheme of the PSAT type III and type IV models should be further investigated, as has been identified as the cause of the worse performance shown by type IV in Chapters 3 and 4. It should also be studied to what extent these control schemes can be modified, as they do not only depend on the structure of the voltage controller, but also on the \( Q \) output of the machine, which is partially determined by the inherent physical characteristics of each type of turbine.

Finally, the study on the influence of the wind farm point of interconnection could be expanded to consider offshore wind farms, given the distinctive characteristics of the connecting subsea cable and their recent increase in popularity.
REFERENCES


BIOGRAPHY OF THE AUTHOR

Luis Badesa was born in Calatayud (Spain) in 1992. He attended high school at IES Leonardo de Chabacier, graduating with honors. He obtained his Bachelor of Science in Industrial Engineering from the University of Zaragoza in 2014, with a concentration in Mechatronics. He joined the Smart Grid Lab at the University of Maine in 2014, as one of the recipients of the Iberdrola Scholarships for Postgraduate Studies in the US. He authored the paper “Impact of Wind Generation on Dynamic Voltage Stability and Influence of the Point of Interconnection”, which was presented in the 2016 IEEE GreenTech Conference, and co-authored the paper “Monitoring Power System Transient Stability Using Synchrophasor Data”, which was presented in the 2015 IEEE Power & Energy Society General Meeting. He is a student member of IEEE Power & Energy Society, as well as a member of Tau Beta Pi, Eta Kappa Nu and Golden Key.

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