



School of Information Technology and
Engineering at the ADA University



School of Engineering and Applied Science
at the George Washington University

FREQUENCY REGULATION WITH RENEWABLE ENERGY INTEGRATION

A Thesis

Presented to the Graduate Program of Electrical and Power Engineering
of the School of Information Technology and Engineering
ADA University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Electrical and Power Engineering
ADA University

By
Gurbanov Gurban

December 2023

THESIS ACCEPTANCE

This Thesis by: Gurbanov Gurban

Entitled: *Frequency Regulation with Renewable Energy Integration*

has been approved as meeting the requirement for the Degree of Master of Science in Electrical and Power Engineering of the School of Information Technology and Engineering, ADA University.

Approved:

(Adviser)

(Date)

(Program Director)

(Date)

(Dean)

(Date)

ACADEMIC INTEGRITY STATEMENT

“I affirm that this is my own work, I attributed where I used the work of others, I did not facilitate academic dishonesty for myself or others, and I used only authorized resources for my thesis, per the ADA University Academic Integrity requirements. If I failed to comply with this statement, I understand consequences will follow my actions. Consequences may range from failing the course to expulsion from the program/university and may include a transcript notation.”

Gurbanov Gurban

(Full Name)



(Signature)

24.12.2023

(Date:
DD.MM.YY)

ABSTRACT

The increasing worldwide focus on integrating renewable energy sources into power grids has attracted significant interest, motivated by the projected benefits of an almost unlimited supply and favorable environmental effects. Among the several choices for renewable energy, wind power emerges as a leading contender, positioned for significant expansion in the foreseeable future. Nevertheless, the incorporation of wind power into current systems presents numerous obstacles, particularly regarding grid stability, despite its acknowledged advantages. The intrinsic qualities of wind power, which include intermittency and non-dispatchability, create complexity in the dynamics of the energy system. The sporadic nature of wind energy source adds further fluctuations to an already changeable frequency deviation landscape, making the issue of maintaining frequency stability even more difficult. The decrease in stability is ascribed to a decrease in system inertia and regulatory capabilities. This research thoroughly examines the diverse impacts of wind and solar power on many components of power system dynamics, such as frequency deviation, stability, tie-line flows, and area control error. The goal is to fully comprehend and examine the consequences of incorporating wind power, particularly as its levels of implementation rise. The findings presented in this research offer valuable perspectives on the complexities of frequency regulation capability under various wind power penetration scenarios. These insights serve as a basis for determining the optimal levels of RES penetration while maintaining specified limits on frequency deviation. The wider framework of incorporating renewable energy, marked by the rapid increase in the installation of wind and solar power, brings about uncertainty to both transmission and distribution systems. The sporadic characteristics of these sustainable sources frequently result in temporary discrepancies between power generation and demand. Historically, the resolution of such discrepancies has entailed augmenting spinning reserves, resulting in significant expenses. The research suggests an inventive method called a dynamic

demand control (DDC) approach that combines primary and secondary methods for regulating frequencies. The core of the suggested technique is the active management of a fraction of the workload to maintain control over the frequency. This method not only tackles abrupt decreases in frequency but also actively aids in aligning the frequency with its intended nominal values. By utilizing dynamic demand control, the demand side of the power equation can efficiently and effectively contribute to frequency regulation, thereby decreasing the requirement for a significant generating reserve and, thus, reducing associated costs. This study provides a comprehensive analysis of the difficulties associated with incorporating wind and solar power into existing power systems. It presents a proactive approach that utilizes dynamic demand control to improve the stability and efficiency of power systems as renewable energy becomes more prevalent.

TABLE OF CONTENTS

LIST OF FIGURES	vii
LIST OF TABLES	vii
LIST OF ABBREVIATIONS	viii
CHAPTER ONE	1
INTRODUCTION	1
1.1 Challenges.....	1
1.2 Solutions	2
1.3 Research objective	3
CHAPTER TWO	5
REVIEW OF THE LITERATURE	5
RESEARCH METHODOLOGY.....	10
3.1 Network stability.....	10
3.2 Frequency response.....	11
3.3 Inertia means in power system.....	13
3.4 Rate of Change of Frequency	16
3.5 Solutions for the frequency response	18
3.5.1 Droop methodologies	18
3.5.2 Fast power reserve	20
3.5.4 Hybrid dynamic demand control strategy	20
CHAPTER FOUR.....	24
SIMULATION AND RESULTS.....	24
4.1 Solar and Wind integration analysis	24
4.2 Load frequency response	28
CHAPTER FIVE	32
CONCLUSION.....	32
APPENDIX.....	34
REFERENCES	35

LIST OF FIGURES

No	Figure Caption	Page
	Figure 3.1. Classification of the power system stability	10
	Figure 3.2. Depiction of the inertial and the frequency responses	11
	Figure 3.3. Characteristics of primary and secondary control	13
	Figure 3.4. Evolution of the frequency a) Nadir and b)RoCoF	17
	Figure 3.5. Diagram illustrating the proposed mechanisms by which renewable energy sources can contribute to the stability of the network	18
	Figure 3.6. Droop technique: Frequency characteristic and block diagram	19
	Figure 3.7. The fast power reserve is determined by two factors: the output power is dependent on rotor speed and the time	20
	Figure 3.9. Frequency response model	21
	Figure 3.10. Reduced response model	22
	Figure 4.1. IEE39 bus system with Wind and Solar Energy integration	25
	Figure 4.2. Frequency fluctuations for per RESs.....	27
	Figure 4.3. Load frequency response: Two-area connected system.	29
	Figure 4.4. RESs penetration level and Frequency response.....	29
	Figure 4.5. RESs penetration level and ROCOF	30
	Figure 4.6. Damping ratio for per RESs	34

LIST OF TABLES

No	Figure Caption	Page
	Table 3.1 Relationship between inertia and the rating of various generator types	15
	Table 3.2 Turbine governor parameters	22
	Table 4.1 Case 1 Zero RES penetration.....	26
	Table 4.2 Case 2 Only Wind power integrated.....	27
	Table 4.3 Case 3 Only Solar power integrated.	26
	Table 4.4 Case 4 Wind and Solar Power integrated	27
	Table 4.5 RES penetration percent and parameters	29
	Table 4.6 RES penetration percent and parameters-area two	34

LIST OF ABBREVIATIONS

Abbreviation	Explanation
RES	Renewable Energy Source
DDC	Dynamic Demand Control
PEC	Power Electronic Converters
PSS	Power System Stabilizers
PV	Solar Photovoltaics
IES	Integrated Energy System
DFIG	Doubly Fed Induction Generator
SG	Synchronous Generators
WT	Wind Turbine
RoCoF	Rate of Change of Frequency
DC	Direct Current
PFC	Primary Frequency Control
SFC	Secondary Frequency Control
TFC	Tertiary Frequency Control
BESS	Battery Energy Storage Systems
TCSC	Thyristor-Controlled Series Compensation
PID	Proportional-Integral-Derivative
SVC	Static Var Compensators
STATCOM	Static Compensators
AGC	Automatic Generator Control
AC	Alternating Current
GND	Ground
RMS	Root Mean Squared

CHAPTER ONE

INTRODUCTION

The application of renewable energy sources (RESs) for power generation poses a wide range of advantages across various sectors, including the environment, finances, technology, society, health, and others. To mitigate the emission of greenhouse gases from thermal power plants, numerous countries have implemented laws aimed at incorporating innovative renewable energy sources (RESs) into their domestic and global electricity networks.

1.1 Challenges

However, renewable energy sources (RESs) have various issues, including significant expenses, limited dependability, flaws in power quality, and difficulties in maintenance due to their dependence on unpredictable weather and environmental circumstances. The unpredictable and sporadic characteristics of renewable energy sources (RESs), such as photovoltaic and wind sources, contribute to the destabilization of the major power system. The issue of unpredictability has emerged as a significant worry in today's energy grid, leading power system developers to adopt a strategy of integrating a considerable proportion of renewable energy sources (RESs) into the main grid. Moreover, it should be noted that these resources utilize Power Electronic Converters (PECs) as fundamental elements, which may give rise to stability concerns. If these problems are not adequately addressed, it could result in the system becoming vulnerable and unsustainable, leading to serious consequences for the operation of the electricity system. Many stability challenges are found in electrical power systems. In the traditional framework, three separate stability concerns are recognized, namely: instability in rotor angle, instability in frequency, and instability in voltage. Out of the three factors mentioned, the maintenance of rotor angle stability is of utmost importance in guaranteeing the synchronization of the system. The requirement for timely resolution in both transient and stable states classifies it as a short-term stability issue.

1.2 Solutions

The effective resolution of this problem can be achieved by utilizing power system stabilizers (PSS) or exciters based on power electronic converters (PEC), supplemented by the use of generator tripping as an alternative approach. Similarly, frequency stability refers to the electrical system's capacity to uphold its operational frequency within acceptable limits. Instability occurs when there are disparities between the supply and demand of electricity. The process of restoring frequency entails a time frame ranging from seconds to several minutes, hence classifying it as a stability concern including both short-term and long-term timeframes. Voltage stability plays a crucial role in maintaining acceptable voltage levels at the receiving end, requiring a time frame of seconds to minutes for restoration. This categorizes voltage stability concerns into short-term and long-term stability issues. In recent decades, there have been notable changes in current power systems, leading to the emergence of new factors affecting power system stability. These factors include converter-driven stability and resonance stability. Power systems that include renewable energy sources (RESs) can experience instability for two main reasons. Firstly, the broad incorporation of energy resources reliant on power electronic converters (PECs), including solar photovoltaics (PV) and wind turbines, reduces the system's inertia. Secondly, RESs face the challenge of balancing the supply and demand chain due to their unpredictable generation patterns. The process of predicting the future values of demand and generation in a time-series context is complex and requires a significant amount of time. As a result, systems often prioritize achieving stability by directing attention towards the demand side. The presence of nonsynchronous generators in conjunction with power electronic converters (PECs) reduces the level of system inertia, hence increasing the likelihood of unstable frequencies in power systems. The proper functioning of electrical systems can be greatly affected by frequency fluctuations, which may result in undesired blackouts, particularly in systems with reduced inertia. The implementation of PEC-

based technologies necessitates the prioritization of upgrading protection equipment in accordance with conventional operational settings. Although there have been numerous research and development endeavors dedicated to stability of the voltage, rotor angle stability, and methods for frequency regulations, the attention given to real-time stability control has been relatively restricted, despite its significant role in causing numerous power system blackouts in recent times.

1.3 Research objective

The increasing intricacy in power system operations, together with the introduction of innovative concepts and regulations, requires the creation of techno-economic methodologies and technologies to ensure Ensuring the secure and dependable functioning of power systems. Numerous research endeavors have put forth diverse ideas to tackle these difficulties; nevertheless, a complex framework that fails to include potential uncertainties may result in unrealistic conclusions, hence introducing complications during the implementation In practical situations or real-world contexts. Thus, it is imperative to conduct a comprehensive investigation into innovative and effective methodologies with the purpose of addressing current and forthcoming issues in the improvement of energy system architecture and also operational strategies. This paper aims to provide a comprehensive comprehension of the stability challenges faced by contemporary power networks as a result of the widespread integration of PEC-based technologies and the unexpected characteristics of renewable energy sources (RESs), such as solar and wind energy. In addition, this work aims to provide a thorough examination of frequency stability concerns and potential remedies, utilizing existing scholarly literature as its primary source of information. The study commences by providing an introduction to the backdrop and a basic review of the stability difficulties encountered by contemporary power systems. Also, provides a comprehensive overview of the substantial amount of previous research conducted by many scholars and institutions. Section 3

extensively explores the principles of frequency stability, encompassing an analysis of responses, regulations, control approaches, and their ramifications for power systems. This examination is complemented by the inclusion of case studies that highlight the importance of frequency stability in contemporary power systems. Furthermore, this study extensively examines the fundamental theme of frequency stability in power systems based on PEC technology. It delves into the complexities surrounding short-term frequency instability and the unique challenges posed by PEC-based technologies in power systems. This section additionally presents potential solutions. The thesis overall serves as a comprehensive summary of the article, wherein the findings and implications are presented and thoroughly examined.

CHAPTER TWO

REVIEW OF THE LITERATURE

The sporadic and fluctuating characteristics of electricity generation from renewable energy sources (RES), together with the fluctuations in net load, present challenges for conventional generation units [1,2]. The concept of variability is perceived differently at each stage of the planning and operational processes. Although the impact of net load variations on long-term resource planning is not significant, the daily cycle remains a crucial consideration in the day-ahead operation plan [1]. During a brief time, frame, typically referred to as the "very short term," the presence of control systems becomes necessary to manage the rapid fluctuations in renewable energy (RE) generation. Electric power systems, which are regarded as a crucial component of large-scale Integrated Energy Systems (IESs), have experienced significant advancements in recent decades. The incorporation of Renewable Energy Sources (RESs) has consistently remained a prominent focus within the realm of development. This is particularly relevant in situations where a significant percentage, or perhaps the entirety, of the energy demand is met by RES generation. In such cases, it becomes necessary for baseload power plants to curtail or cease their generation activities. Nevertheless, it is imperative to redistribute these plants to align with the prevailing demand, while concurrently reducing the development of renewable energy sources (RES). This is a significant issue as the commencement periods of coal or nuclear power facilities are too prolonged [3]. Consequently, the expenses related to operating and maintaining power plants, as well as the costs associated with fuel, experience an upward trend, while the anticipated lifespan of these plants undergoes a decline. Additionally, it is worth noting that the occurrence of plant outages for maintenance has been seen to be more frequent, as indicated by previous studies [4,5,6]. It is anticipated that there will be a shift towards low-carbon solutions in base-load plant technologies in the future, considering the implementation of carbon regulations and constraints. A further noteworthy

aspect to consider is the necessity for increased flexibility compared to currently available technologies . Based on the findings of Holttinen's study, the integration of wind power at a 10% penetration level in Scandinavian nations increases the reserve demand ranging from 1.5% to 4% of the total installed wind power capacity. A higher degree of renewable energy (RE) integration into the power system can be achieved by reducing the minimum power output requirement of power plants that are capable of meeting the demand. This adjustment would enable a greater level of RE penetration without necessitating the shutdown of existing power plants. Hence, in addition to the heightened reserve requirements, the minimum power outputs of the power plants may also give rise to challenges in the immediate term Hossain et al. [7,8] have reported that Doubly Fed Induction Generator (DFIG) turbines exhibit limitations in their ability to provide reactive power and create substantial short-circuit currents when compared to Synchronous Generators (SG). The study also examined the effects of a significant increase in wind power penetration on the transient and frequency stabilities of a power system using a 39-bus test system. The study revealed that transient stability experiences a negative impact when a fault occurs in proximity to an area characterized by strong wind penetration. The primary factor contributing to this phenomenon is the decrease in active power generation and the concurrent rise in reactive power absorption observed during the implementation of crowbar protection in situations where wind turbines are operating at less than full capacity. In instances where a failure occurs close to synchronous generators (SGs), it has been discovered that wind turbines (WTs) enhance transient stability by contributing to the power flow required for synchronizing forces throughout the network. Different levels of penetration, ranging from low to high, have been investigated, considering an installed power capacity of up to 2000 MW. The researchers evaluated the levels of penetration, while maintaining the presence of SGs within the system. The simulations indicate that the stability of the system frequency is negatively impacted when the penetration level reaches 20%.

The time difference between zero crossings of the voltage waveform is commonly used to calculate frequency. More than two zero crossings can be used to determine accurate and reliable frequency measurement. Other considerations must be considered before deciding on the time range during which frequency should be measured (and upon which protection schemes should operate). The first is whether the faults are symmetrical or asymmetrical (single or three-phase) near the frequency measurement. The distorted voltage waveform may cause incorrect detection of zero crossings. A second consideration is inter-area oscillation events, which cause abrupt changes in frequency and may result in incorrect frequency readings. Frequency fluctuations of a significant magnitude can cause load shedding, instability, equipment damage, and even blackouts. In recent years, the power industry has become more concerned about the falling quantity of inertia and primary frequency response in many interconnections. Because of the increasing penetration of inverter-coupled production and the projected retirement of conventional thermal facilities, this drop could continue. Because of the high reaction speed from the power electronics interfaces, VRE controllers can give superior primary, secondary, and tertiary responses to traditional generators if appropriately built. The inertial reaction is the instantaneous response to a power disturbance caused by a change in frequency. By lowering the rate of change of frequency immediately following a disturbance, this is a crucial determinant of both transient stability and tiny signal stability. Synchronous machines give inertial responses to power systems by default. Active power controllers for VRE can give a synthetic inertia response to stabilize frequency excursions if properly built [9,10]. The controller design is guided by various frequency indices, including the rate of change of frequency (ROCOF), frequency deviation, and a combination of frequency deviation and ROCOF. Consequently, the wind turbine (WT) accelerates or decelerates in response to disturbances so as to store or release the rotational kinetic energy under the control of the rotor kinetic energy. Nevertheless, the kinetic energy

is constrained, and a secondary frequency decline may occur when the rotor speed returns to its initial level [11]. Concurrently, pitch activation is ongoing. The majority of renewable energy sources employ frequency deviation signals and ROCOF to regulate the additional power applied to the power reference [12], [13]. The authors of [13], for instance, obtained frequency regulation through the utilization of frequency deviation and ROCOF to control the DC-link voltage. ROCOF is employed by additional researchers to accomplish virtual inertia control.

Traditional power grid synchronous generators have good inertia and damping characteristics, absorbing or releasing energy via inertial response to preserve system frequency stability [14,15]. As renewable energy develops, large-scale renewable energy is incorporated into the power grid via power electronic equipment. The power system is evolving in a low inertia direction. In general, renewable energy does not require any particular grid-connection regulations to supply primary frequency regulation capacity. As a result, renewable energy cannot provide power systems with stability and effective inertia support [16,17]. The impact of expanding the network's RES has resulted in a significant demand for spinning reserves, which are required to balance the deviations caused by variable generation. Low levels of rotational inertia in a power system, which are induced by inverter-connected RES with zero or minimal inertia, affect frequency dynamics in the sense that they occur more rapidly in such systems. As a result, conventional frequency control schemes become excessively sluggish in their ability to disrupt significant frequency deviations and the subsequent detrimental effects they cause. New phenomena of frequency instability may result from the loss of rotational inertia and time variance of inertia [18].

The frequency of the load is a key indicator of the reliability of a power grid. Grid frequency is measured continuously to track the stability of the power system's supply and demand ratio. To guarantee the safe and reliable operation of the power system, the nominal value of the grid

frequency must be kept at either 50 or 60 hertz (depending on the country's operating policy), with an upper and lower operating limit of $\pm 1\%$ hertz. Primary frequency control (PFC), secondary frequency control (SFC), and tertiary frequency control (TFC) are the control loops used to regulate the grid's frequency (within a given frequency deviation range). Power-electronics-interfaced generating technologies, such as wind and solar PV, have dramatically expanded their proportion of global generation in the recent decade. Studies have shed light on the impact of the high-penetration RES' integration on the stability of the power system in different countries. Modern power systems are increasingly focused on techno-economic functioning, together with environmental limitations. The regulatory authority can replace the control system with an optimized method and/or add an optimized supervisory system without modifying the main system to improve operational restrictions [19]. Nevertheless, as the integration of RES and PEC-based technologies continues to rise, current power systems encounter new challenges, including issues like unbalanced frequency resilience and reduced grid inertia [20]. Therefore, it is essential to implement tools that can dynamically monitor, analyze, enhance, and visualize the characteristics of the system [21]. It is obvious that traditional methods of control are inadequate for today's power grids, hence a fresh approach is required. In [22,23], the idea of battery energy storage systems (BESSs) was applied to controlling the frequency of an electrical grid. Employing fuzzy logic in conjunction with thyristor-controlled series compensation (TCSC), a self-tuning proportional-integral-derivative (PID) controller was created to improve transient stability. Similarly, a controller based on neural networks and fuzzy logic was proposed. The first-swing stability of power systems can be enhanced with a discontinuous control approach and devices like static VAR compensators (SVCs) and static compensators (STATCOMs) [24,25,26].

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Network stability

The concept of stability in a power network refers to the ability to sustain a state of permanent operating equilibrium. This entails the maintenance of consistent voltages and frequency, as well as the preservation of synchronism among synchronous machines. In order to maintain system robustness and ensure reliable and secure operation, it is imperative that all of these conditions are met [27]. The primary system parameters, depicted in the diagram seen in Figure 3.1, comprise frequency, voltage, and rotor angle. The concept of angle stability can be categorized into two distinct types: tiny-signal stability refers to the ability of a system to maintain stability under tiny disturbances or fluctuations. Transient stability, on the other hand, refers to the ability of a system to maintain stability after experiencing a large disturbance or fault. Voltage stability, on the other hand, is examined based on the size of the disturbance. Additionally, each system parameter is described by either a short-term or long-term time frame, with the exception of the angle limit.

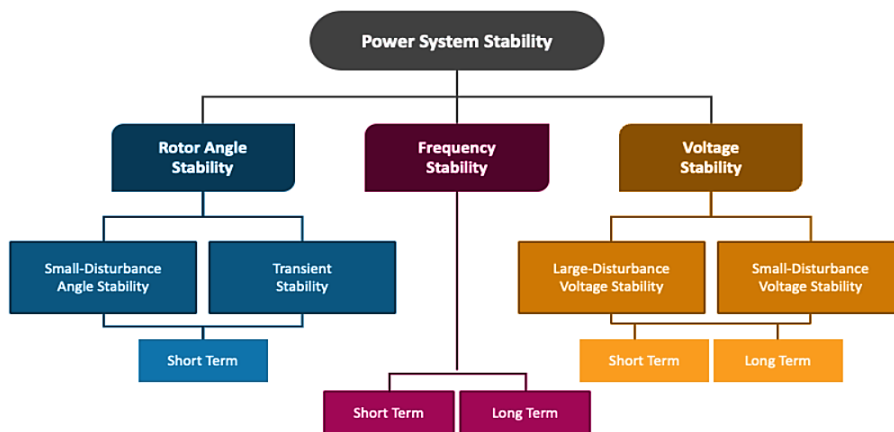


Figure 3.1. Classification of the power system stability [27]

When a network power imbalance happens, the system frequency control is used to bring the system frequency back to a steady state use sluggish centralized controllers, also known as

Automatic Generator Control (AGC) or secondary maintenance, and to stabilize it using fast-acting closed-loop controllers, such as governors involved in main frequency reserves.

3.2 Frequency response

A disbalance in an alternating current (AC) network is characterized by a discrepancy between the generated and produced powers. Depending on the geographical location, the grid frequency will be either increase or decrease from its nominal value of 50 or 60 Hz. To rectify this alteration and reinstate the frequency to its intended level, system administrators have executed three main frequency control drawings, with each scheme contributing to the system restoration within a designated time interval. In fact, for the stability of the system, the grid frequency must remain within a permissible range or 5% deviations from the nominal value [28]. Significant frequency deviations have the potential to induce grid disruptions, which may culminate in fault cascades or complete outages. The various forms of frequency responses following a frequency dip are depicted in Figure 3.2 together with the respective time intervals.

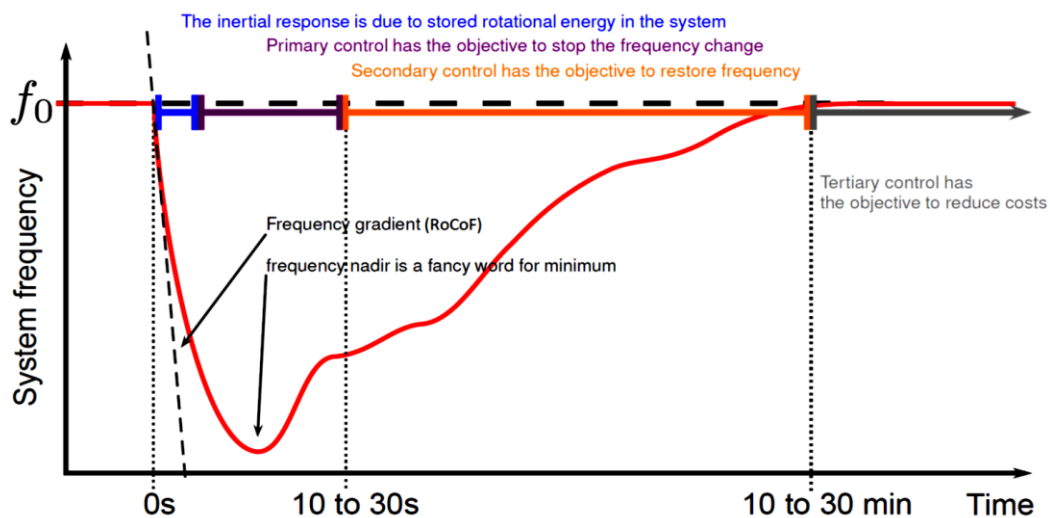


Figure 3.2. Depiction of the inertial and the frequency responses [28]

Initially, the frequency decline is constrained by the inertia of the synchronous generator that are connected to the power grid, prior to any frequency response of the governors. This is referred to as the grid's inertial response. This response takes effect during milliseconds to a

few of seconds following the onset of the imbalance and is contingent on the inertia of the system as a whole, which attenuates the frequency deviation from its nominal value.

Primary frequency reserves are the initial reserves that are automatically activated in relation to the frequency response of the regulator. These phenomena manifest in a matter of seconds, usually between 10 and 30 seconds following the imbalance's occurrence. The system comprises a governor that active power regulation the synchronous machine involved in the frequency response. This adjustment is made in response to the local frequency variation, with the ultimate goal of diminishing the frequency deviation and ensuring the frequency stability of the system. When the frequency of the AC region is shared, the generators will modify their output power irrespective of the location of the power imbalance. The generators' response is determined by their frequency-droop properties, which provides insight into the variation in active power produced in response to a frequency change [28]. Secondary frequency reserves, similar to the initial frequency reserves, occur routinely thereafter. These reserves, alternatively referred to as Automatic Generation Control (AGC), have a duration of 10 to 30 minutes. Their objective is to reinstate Adjust the grid frequency to its designated value and reinstate the power exchanges between tie-lines to their designated values in the other control zones. In order to restore the frequency, these reserves are engaged via an integral controller that modifies the turbine governor set points. It can be seen from Figure 3.3 deploying proper control method is used to restore frequency to its initial nominal value.

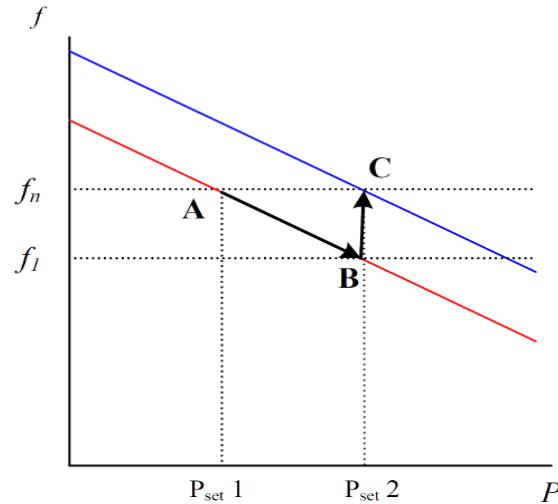


Figure 3.3. Characteristic of primary and secondary control [42]

Between two set points are the area which is control method started to load shedding and tripping designated loads. Tertiary frequency reserves denote the ultimate phase of frequency regulation. These occur subsequent to the cessation of secondary reserves operations and involve the manual distribution of generated power to designated operating locations, alongside the coordination of power production to address current and future system disturbances and prevent congestion. Emergency control and protection schemes, such as load shedding, may be activated for this purpose. In addition, it is possible to manually reschedule the generator using less expensive sources within 45 to 75 minutes of the imbalance occurring [29]. In this study, this type of frequency response is not investigated. Thus, frequency reserves are contingent upon a number of system parameters, including the headroom, the percentage of MW size trips, the availability and withdrawal of governor control, The velocity of the principal frequency response, the frequency controllability of asynchronous machines and their connections also the availability of fast-acting energy storage plants.

3.3 Inertia means in power system.

Synchronous generators, commonly found in the traditional power sources such as clear, coal, gas, and hydropower, the system has rotating masses that are directly linked to the inertial frequency response. This connection is a result of their electromechanical coupling. The

spinning masses in question exhibit a specific level of kinetic energy. When there is a departure in deviation from the desired frequency. The synchronous generator can either absorb or inject kinetic energy into the grid, depending on the circumstances. This measure aims to reduce the occurrence of frequency deviation [30]. The equivalent inertia is determined by the ratio of the rotational energy. (E_k) at nominal speed ω_0 in (J) to the rated power of the generator (S) in megavolt-amperes (MVA).

$$H = \frac{E_{k,0}}{S} = \frac{1}{2} \frac{J\omega_0^2}{S} \quad (3.1)$$

The measurement of inertia, expressed in seconds, quantifies the duration for which a synchronous machine can provide its rated power by utilizing the kinetic energy stored in its spinning masses. According to the source [31], inertia can be described as the property of a physical object that resists changes in its motion, specifically with regard to modifications in its velocity and trajectory. In the present scenario, the rotating masses and its the resistance may be considered physical entities. The resistance towards the alteration in rotational velocity can be associated with the moment of inertia. The inertia of a machine is contingent upon its kind, size, and velocity. Table 3.1 displays the customary values, which span a range of 2 to 10 seconds, illustrates the relationship between inertia and the rating of various generator types. It is seen that inertia generally exhibits an inverse proportionality to the machine's rating, which is directly linked to Equation 3.2.

Table 3.1. Relationship between inertia and the rating of various generator types [31]

Power plant	Rating S [MW]	Inertia H [s]
Thermal	500 - 1500	2 - 2.3
Thermal	1000	4 - 5
Thermal	10	4
Thermal	Not mentioned	4 - 5
Thermal (2 poles)	Not mentioned	2.5 - 6
Thermal (4 poles)	Not mentioned	4 - 10
Thermal (steam)	130	4
Thermal (steam)	60	3.3
Thermal (combined cycle)	115	4.3
Thermal (gas)	90 - 120	5
Thermal	Not mentioned	2 - 8
Hydroelectric ($450 < n < 514$ rpm)	10 - 65	2 - 4.3
Hydroelectric ($200 < n < 400$ rpm)	10 - 75	2 - 4
Hydroelectric ($138 < n < 180$ rpm)	10 - 90	2 - 3.3
Hydroelectric ($80 < n < 120$ rpm)	10 - 85	1.75 - 3
Hydroelectric	Not mentioned	4.75
Hydroelectric ($n < 200$ rpm)	Not mentioned	2 - 3
Hydroelectric ($n > 200$ rpm)	Not mentioned	2 - 4
Hydroelectric	Not mentioned	2 - 4

By employing Equation 3.1, one can first-order approximate the swing equation at nominal frequency ω_0 in terms of inertia H .

$$\frac{2HS}{\omega_0} \frac{d\omega}{dt} = \frac{2HS}{f_0} \frac{df}{dt} = P_{m,0} - P_e \quad (3.2)$$

This indicates that the inertial response of the power system following a disbalance is proportional to the rate of change of frequency df/dt caused by a power imbalance $P_{m,0}-P_e$. Inertia H is thus directly proportional to this rate of change. In fact, the mechanical of rotational speed is directly proportional to the angular frequency due to synchronism. Generators are therefore outfitted with a speed governor, which consisting of a tachometer that determines the angular velocity of the shaft, as well as a motor known as a servomotor, which regulates the flow of fluid to the turbine via a throttle, so as to participate in frequency control. Each of them modifies its load angle and velocity in response to the disturbance following its inertia and

electric distance. Based on the results of Equation 3.2, it can be deduced that a system with low inertia will exhibit less dampened frequency changes and greater frequency fluctuations in comparison to a network with high inertia [32]. In addition, rotating masses provide stored energy and serve as a voltage source for synchronous machines, which safeguards against fluctuations in the magnitude of voltage and supplies power sources that also can be utilized to restrict voltage fluctuations. As a result, inertia is a crucial parameter that affects the frequency and voltages of the power system.

3.4 Rate of Change of Frequency

The initial Potential repercussions emphasized regarding the network is directly associated with the Rate of Change of Frequency (ROCOF). It is derived directly from the swing equation derived in Equation 4.1, assuming no frequency-dependent burden exists, and corresponds to the frequency derivative immediately following the disturbance.

$$ROCOF = \frac{df}{dt} = \frac{\Delta Pf_0}{2HS} \quad (4.1)$$

denoted by P the power imbalance caused by the disturbance and H the inertia of the system as defined in equation 4.1 Based on this correlation, it can be inferred that systems with low inertia are susceptible to substantial frequency deviations, which can compromise the stability of the system and potentially result in network complications. Because dynamics are more rapid, it becomes more difficult to regulate the electrical system besides, it is necessary to adjust the frequency. Furthermore, numerical protection relays are integrated into the energy system to avoid islanding, and their proper tripping is determined by the means of the ROCOF, which corresponds to the biggest frequency variation following a disturbance. If it is too high, equivalent to a too steep frequency deviation, and reaches a threshold value, the relay gives a trip to protect mechanically limited synchronous machines. In a low inertia system, a significant Rate of Change of Frequency (ROCOF) can activate these specific relays and cause dispersed generation to disconnect in a chain reaction., potentially amplifying The occurrence

of the original frequency incident can result in equipment damage. For example, in [33], various simulations in a two-area connected system experiencing a reduction in inertia were performed. As a result, transient flows across the tie-line between the two locations increased significantly and became more abrupt. The grid could perceive these results as a short circuit, resulting in automatic protection device tripping. Furthermore, low inertia combined with a very high RoCoF can result in a significantly lower frequency nadir. Both are depicted in Figure 3.4 as a function of converter 2 connected generation with an imbalance of 0.1 pu for various system synchronous machine inertia values. When an imbalance occurs, creating a frequency drop, the frequency nadir is defined as the lowest frequency reached, for instance When the generated electricity is insufficient compared to the power used. In a low inertia system, fewer governors participate in frequency control, and the remaining governors experience a reduced amount of time to respond, resulting in a lower frequency nadir than in a higher inertia situation. When the frequency increases, the same effect occurs, with the maximum frequency being much greater in low inertia systems. If the frequency nadir is excessively low, frequency relays can trip, resulting in under-frequency load shedding, potentially leading to cascaded disruptions, and, in the most severe case, complete blackouts.. In the event of a low frequency nadir, generators may be disconnected and load shedding may ensue, jeopardizing system stability [34].

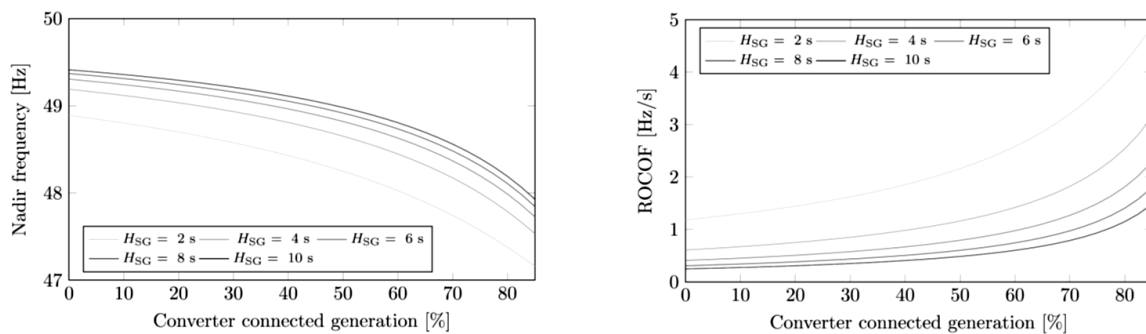


Figure 3.4. Evolution of the frequency a) Nadir and b) RoCoF [33]

3.5 Solutions for the frequency response

In addition to inertial response, frequency and voltage regulation techniques must be implemented in a system with minimal inertia. Certain methods or devices may be utilized in conjunction with RES to maintain network stability. The methods depicted in Figure 3.5 comprise droop control, rapid power reserve, inertia emulation, demand response, synchronous condenser utilization, and modification of existing protection relays. A comprehensive explanation of each is provided in the subsequent subsections.

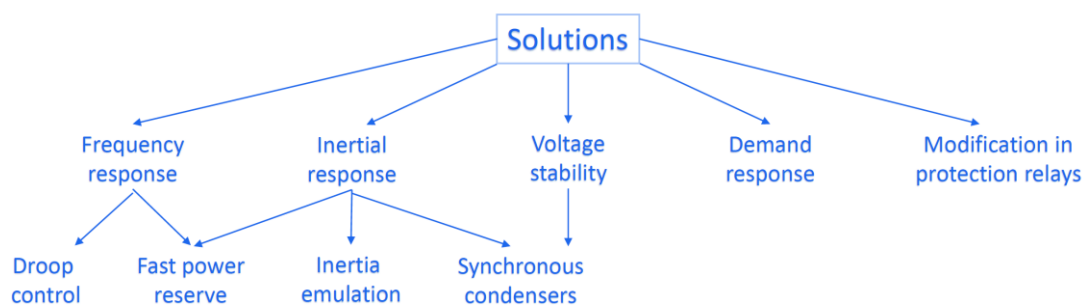


Figure 3.5. Diagram illustrating the proposed mechanisms by which renewable energy sources can contribute to the stability of the network [43]

3.5.1 Droop methodologies

As opposed to synchronous machines, dropping methods are the initial category of frequency regulation methods that can be integrated into the controller of a RES in order to enable it in order to engage in frequency control. Regarding traditional synchronous generators that are outfitted with a governor, a perturbation in the network's frequency is converted into a modification in power output, such as that observed in a wind turbine. This transformation adheres to the pattern illustrated in Figure 3.6a. By employing this method, the wind turbine can engage frequency reserves, which serve to enhance the frequency nadir and facilitate the restoration of the frequency to its nominal value. The subsequent equation calculates the the change in output power of wind turbine P, where the change is proportional to the frequency ($f = f_{\text{meas}} - f_{\text{nom}}$).

$$\Delta P = P - P_0 = -\frac{f_{meas} - f_{nom}}{R} \quad (5.1)$$

In the given equation, P represents the WT's dispatched output power, f_{meas} denotes the measured grid frequency, and R signifies the droop characteristic's chosen droop coefficient. P_0 and f_{nom} represent the rated active output power and power station frequency, respectively. The droop control block diagram is illustrated in Figure 3.6b. The power converter of the turbine receives the signal $P_{ref} = P_{MPP} + P$, which specifies the quantity of stored kinetic energy that must be discharged.

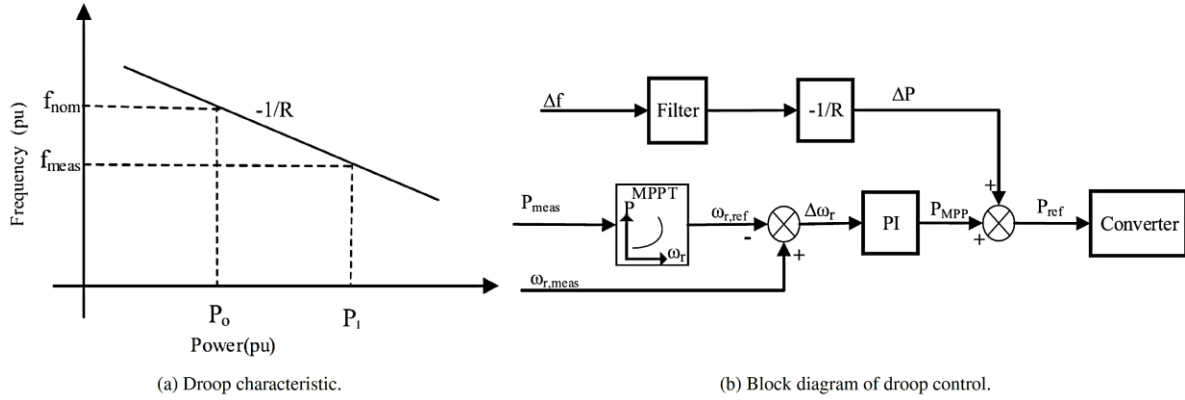


Figure 3.6. Droop technique: Frequency characteristic and block diagram [36]

Emphasis is placed on this control for PVs in [35], which implements an active and reactive droop control in conjunction with an ESS. To engage in frequency and voltage controls, the system automatically adjusts both active and reactive powers within the grid whenever PV arrays fail to generate. In the event that the demand exceeds the generated power, the inverter control transitions to modulate the frequency and voltage in accordance with the set parameters for active and reactive power. However, droop control necessitates the establishment of a linear correlation between reactive power and voltage and active power in relation to frequency. As a result, computations requiring brief timescales are required to slow down the droop-controlled inverters, specifically their transient response [36,37].

3.5.2 Fast power reserve

A different possible solution for temporary inertial response and frequency assistance is the rapid power reserve technique, which is exclusive to wind turbines. As depicted in Figures 3.7a and 3.7b, the operational mechanism of the technique is as follows: when the frequency deviation surpasses a specific threshold during a decrease in frequency, from P_{MPPT} , the wind turbine's maximum power point tracking, to P_{cmd} , its output active power increases. Additionally, In the time interval t_{dec} , it feeds the grid the kinetic energy that has built up in its spinning blades, which causes the rotor speed to decrease to Ω_{Tmin} . The time period in which the wind turbine engages in frequency regulation is referred to as the over-production period. Subsequently, the wind turbine resumes normal operation during t_{acc} by reducing its output generation power and restoring its nominal rotor speed to MPPT.

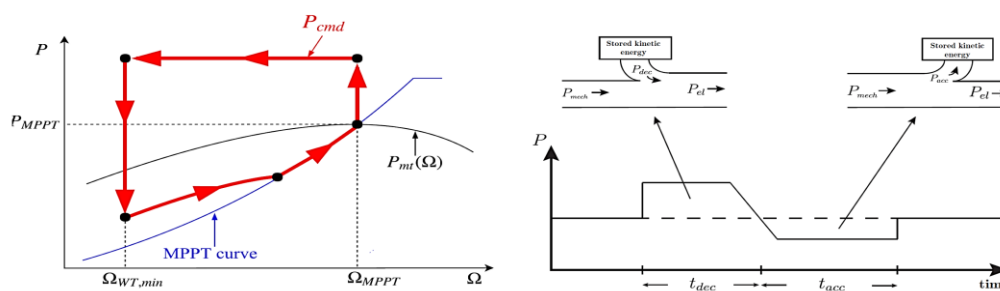


Figure 3.7. The fast power reserve is determined by two factors: the output power is dependent on rotor speed and the time [27]

The primary limitation of this method continues to be its short-term functionality, given that the wind turbine cannot engage in frequency regulation for extended durations, particularly during its recovery or underproduction phase. Therefore, the extent to which the wind turbine operates is contingent upon the quantity of kinetic energy contained in its rotating masses.

3.5.4 Hybrid dynamic demand control strategy

An imbalance in power generates frequency dynamics in a power system. The system operates in accordance with the principles of motion when variations in local frequencies

induced by oscillations and transients in electromechanical systems are disregarded. When this law is applied to deviations from nominal values, it yields [37]:

$$\Delta P_g(t) - \Delta P_d(t) = 2H \frac{d\Delta f(t)}{dt} + D\Delta f(t) \quad (5.2)$$

The variables $\Delta P_g(t)$, $\Delta P_d(t)$, and $\Delta f(t)$ represent the deviations of load demand and deviation of the power system frequency from its nominal value at period t , respectively, and the generator mechanical power and load demand, respectively, from their pre-disturbance values and the nominal value at time t , respectively ($\Delta f(t) = f(t) - 60$). Unit values are provided for the power and frequency variables. The system's total inertia constant is denoted by H . Synchron machines and frequency-dependent loads, such as induction motors, provide a substantial contribution to the overall load-damping coefficient (D) of the system. The entire system frequency-responsive model is made up of the lumped generator turbine regulator and the lumped time-dependent load., as illustrated in Figure 3.9a the power imbalance denoted as $\Delta P = P_g - P_d = \Delta P_g - \Delta P_d$, is an indication of the effect of an abrupt load change or generation decrease. The value of ΔP can be negative or positive. As shown in Table 2 are the typical turbine governor parameters. Simplifying the analytical analysis, we can disregard T_G and T_C as they are significantly smaller in magnitude than T_R . As illustrated in Figure 3.10b [38], afterwards decreases the transfer function model's order.

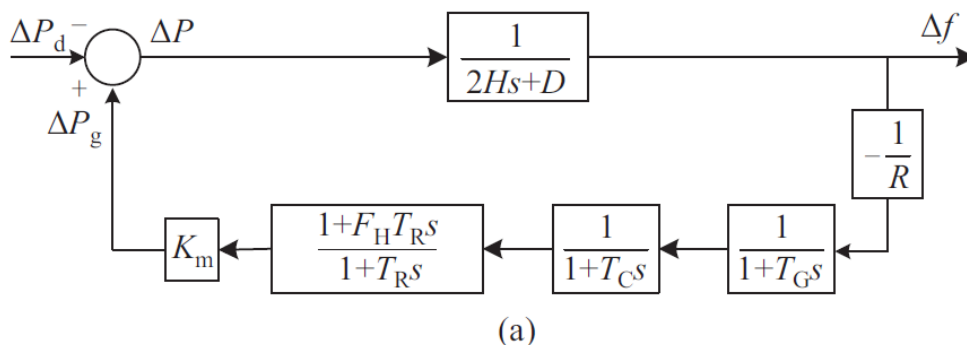


Figure 3.8. Frequency response model [44]

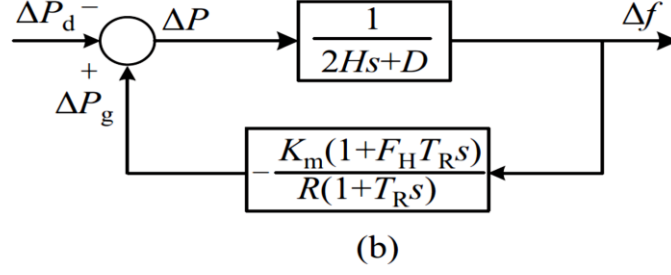


Figure 3.9. Reduced response model [44]

Table 3.2 Turbine governor parameters [42]

Parameter	Typical Value
Governor time constant T_G	0.2 s
Steam chest time constant T_C	0.3 s
Reheat time constant T_R	10 s
High-pressure turbine fraction F_H	0.3
Mechanical power gain factor K_m	0.95–1
Inertia constant H	3–6 s
Governor speed regulation R	0.05
Load damping coefficient D	1.0

A negative ΔP causes a decrease in the system frequency, after which it returns to a state of equilibrium. The frequency response of the system can be described by three time-domain parameters, which are comparable to the step response of the standard second-order dynamic system: steady-state frequency f_{ss} , time to reach frequency nadir t_{nadir} (which corresponds to maximal overshoot), and frequency nadir (or time to reach) f_{nadir} . The Laplace transform of FR is computed as shown in Figure 10b.

$$\Delta f(s) = \frac{R\omega_n^2}{DR + K_m} \cdot \frac{K_m(1 + F_H T_R s) \Delta P}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad (5.3)$$

where ζ represents the damping coefficient and ω_n represents the oscillation frequency. The aforementioned values are derived from the turbine governor parameters.

$$\omega_n^2 = \frac{DR + K_m}{2HRT_R} \quad (5.4)$$

$$\zeta = \frac{2HR + (DR + K_m F_H)}{2(DR + K_m)} \omega_n \quad (5.5)$$

Inverse Laplace transform is utilized to acquire the time-domain frequency deviation.

$$\Delta f(t) = 60 \cdot \frac{R\Delta P}{DR + K_m} [1 + ae^{-\zeta\omega_n t} \sin(\omega_r t + \varphi)] \quad (5.6)$$

a and ω_r defined as follow:

$$a = \sqrt{\frac{1 - 2T_R\zeta\omega_n + T_R^2\omega_n^2}{1 - \zeta^2}} \quad (5.7)$$

$$\omega_r = \omega_n \sqrt{1 - \zeta^2} \quad (\zeta < 1). \quad (5.8)$$

At the point of lowest frequency, the derivative of the frequency graph should be equal to zero, expressed as $d\Delta f(t)/dt = 0$. Hence, the value of t_{nadir} is derived by the process of calculation.

$$t_{\text{nadir}} = \frac{1}{\omega_r} \tan^{-1} \left(\frac{\omega_r T_R}{\zeta\omega_n T_R - 1} \right). \quad (5.9)$$

The frequency deviation reaches its new equilibrium state, which is

$$\Delta f_{\text{ss}} = 60 \cdot \frac{R\Delta P}{DR + K_m} \approx 60 \cdot \frac{R\Delta P}{DR + 1}. \quad (5.10)$$

On the basis of (5.6) and (5.9), the following can be stated regarding the frequency response of the energy system:

- 1) The t_{nadir} is influenced by the inertia of the generator, turbine governor parameters, and system damping. T_{nadir} has no connection to ΔP .
- 2) In real time, the frequency response $\Delta f(t)$ is likewise multiplied by value of K when ΔP is multiplied by a coefficient K .
- 3) F_{nadir} is proportional to ΔP if the dynamic power system parameters (listed in Table 2) remain unchanged, as indicated by two preceding arguments. Due to its complexity, the analytical expression of Δf_{nadir} is omitted here.

CHAPTER FOUR

SIMULATION AND RESULTS

4.1 Solar and Wind integration analysis

The methodology that was suggested is executed and evaluated on the power grid of the IEEE39 bus system, as depicted in Figure 4.1. The power infrastructure is made up of ten generators and thirty-nine buses. An exhaustive list of system parameters is available in the literature [38,39,40]. The methodology that has been proposed was developed and evaluated within the MATLAB 2023b environment. The buffering characteristics of interconnected systems, specifically those comprising a wind farm and a photovoltaic (PV) system, are the primary emphasis of the analysis. Eigenvalue analysis is performed for four distinct working conditions as part of the analysis.

1. System Initial:

This depicts the power system in its fundamental configuration, devoid of any supplementary renewable energy sources.

2. Bus #1 Connects exclusively wind farms that have a maximum output of 100 MW:

Wind turbines are exclusively connected to bus #1 in this scenario, producing a total output of 100 MW.

3. Bus #2 is exclusively connected to the PV system, which generates 80 MW.

4. The PV system and wind turbines are connected on bus #2 and bus #1, respectively, with outputs of 50 MW and 50 MW.

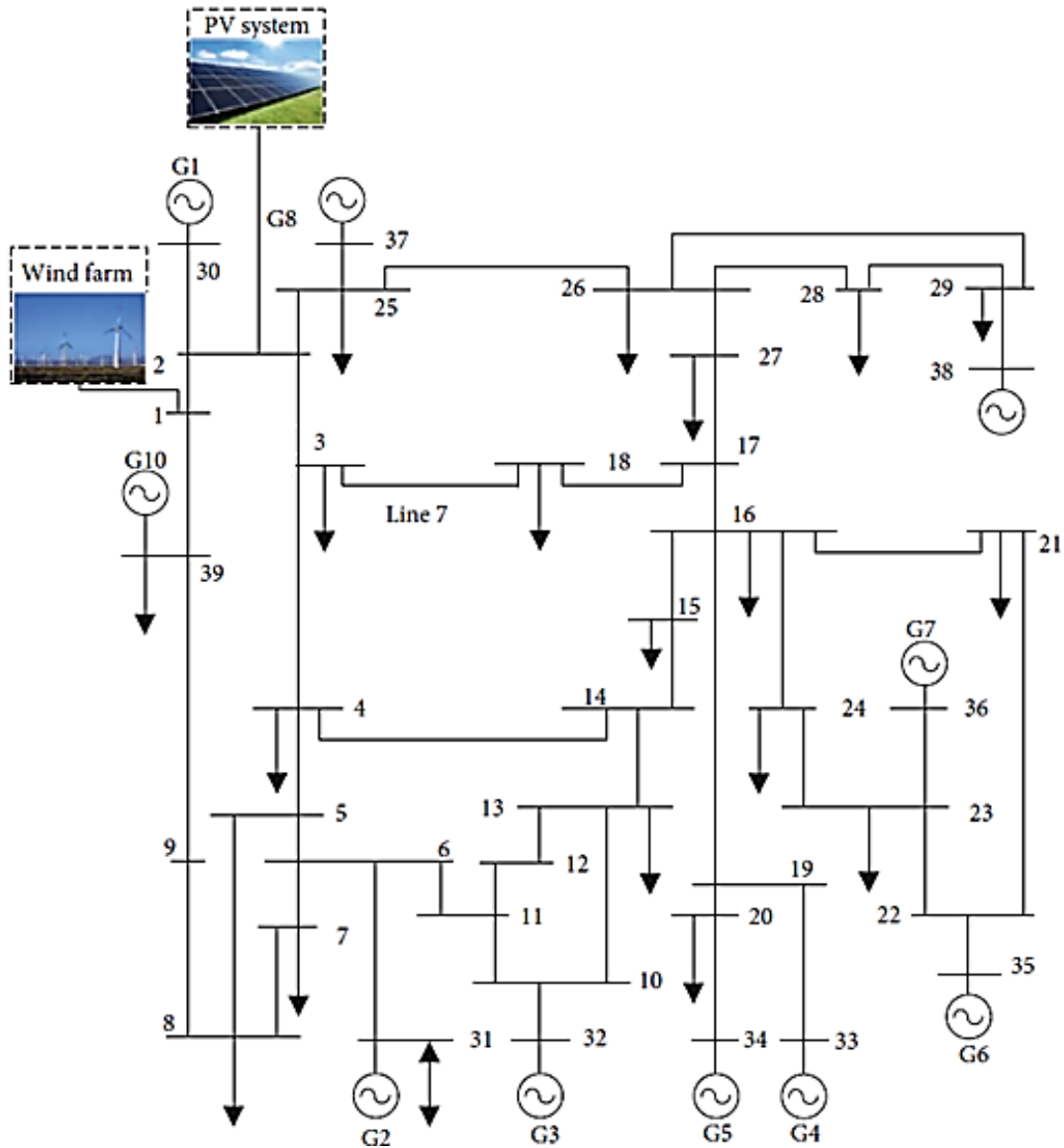


Figure 4.1 IEEE39 bus system with Wind and Solar Energy integration [39]

Table 4.1. Case 1 Zero RES penetration.

Case	Characteristic root	frequency fluctuations (Hz)	Damping ratio	Relevant units
Without Wind or Solar power	$-0.9999 \pm j6.8994$	1,0985	0,1458	G1, G2
	$-1.2415 \pm j7.4895$	1,2373	0,1632	G1, G3
	$-0.3041 \pm j4.1508$	0,6624	0,078	G1, G5
	$-0.8543 \pm j7.1886$	1,0105	0,1348	G1, G8
	$-0.5404 \pm j7.9944$	0,9517	0,0919	G1, G9
	$-0.4333 \pm j4.4617$	0,7978	0,0874	G1, G10
	$-0.6732 \pm j6.6944$	0,8197	0,1310	G2, G3
	$-1.1864 \pm j6.2942$	0,7443	0,248	G2, G4

Table 4.2 Case 2 Only Wind power integrated.

Case	Characteristic root	frequency fluctuations (Hz)	Damping ratio	Relevant units
Wind Power	$-1.1794 \pm j7.1987$	1,1833	0,1643	G1,G2
	$-1.3958 \pm j7.9994$	1,3017	0,1756	G1,G3
	$-0.5308 \pm j4.4898$	0,7636	0,1183	G1,G5
	$-1.0552 \pm j6.6954$	1,1022	0,1581	G1,G8
	$-0.7319 \pm j6.2952$	0,9995	0,1176	G1,G9
	$-0.4433 \pm j5.0128$	0,8003	0,0891	G1,G10
	$-0.6928 \pm j5.1704$	0,8621	0,1341	G2,G3
	$-1.2822 \pm j4.8332$	0,8077	0,2585	G2,G4
	$-1.1228 \pm j7.2706$	1,1948	0,1552	G2,G5
	$-0.4511 \pm j0.8102$	0,1677	0,4794	G1-10,DFIG

Table 3.3 Case 3 Only Solar power integrated.

Case	Characteristic root	frequency fluctuations (Hz)	Damping ratio	Relevant units
Solar Power	$-1.3968 \pm j7.5559$	1,1985	0,1826	G1,G2
	$-1.5461 \pm j8.1922$	1,3073	0,1857	G1,G3
	$-0.7978 \pm j4.8928$	0,7829	0,158	G1,G5
	$-1.2907 \pm j7.0776$	1,1235	0,1799	G1,G8
	$-1.0425 \pm j6.7985$	1,0796	0,1516	G1,G9
	$-0.5817 \pm j5.3105$	0,8426	0,1147	G1,G10
	$-0.8103 \pm j5.3630$	0,8511	0,1481	G2,G3
	$-1.3359 \pm j4.9240$	0,7781	0,2619	G2,G4
	$-1.2851 \pm j7.5961$	1,2064	0,1617	G2,G5
	$-0.7107 \pm j1.2256$	0,1926	0,4929	G1-G0,PV

Table 4.4. Case 4 Wind and Solar Power integrated.

Case	Characteristic root	frequency fluctuations (Hz)	Damping ratio	Relevant units
Combination of Solar and Wind power	$-1.4858 \pm j7.7576$	1,2321	0,1925	G1,G2
	$-1.5323 \pm j8.2386$	1,3144	0,1879	G1,G3
	$-0.8778 \pm j5.0250$	0,8004	0,1684	G1,G5
	$-1.2968 \pm j7.1115$	1,1357	0,1832	G1,G8
	$-1.0858 \pm j6.9001$	1,1022	0,1604	G1,G9
	$-0.7568 \pm j5.4995$	0,8776	0,1319	G1,G10
	$-0.9275 \pm j5.5895$	0,8926	0,1658	G2,G3
	$-1.4402 \pm j5.0987$	0,8166	0,2753	G2,G4
	$-1.5488 \pm j7.9968$	1,2761	0,1951	G2,G5
	$-0.8192 \pm j1.4506$	0,2940	0,4978	G1-G10,DFIG
	$-0.7313 \pm j5.0705$	0,80105	0,1473	G1-G10,PV

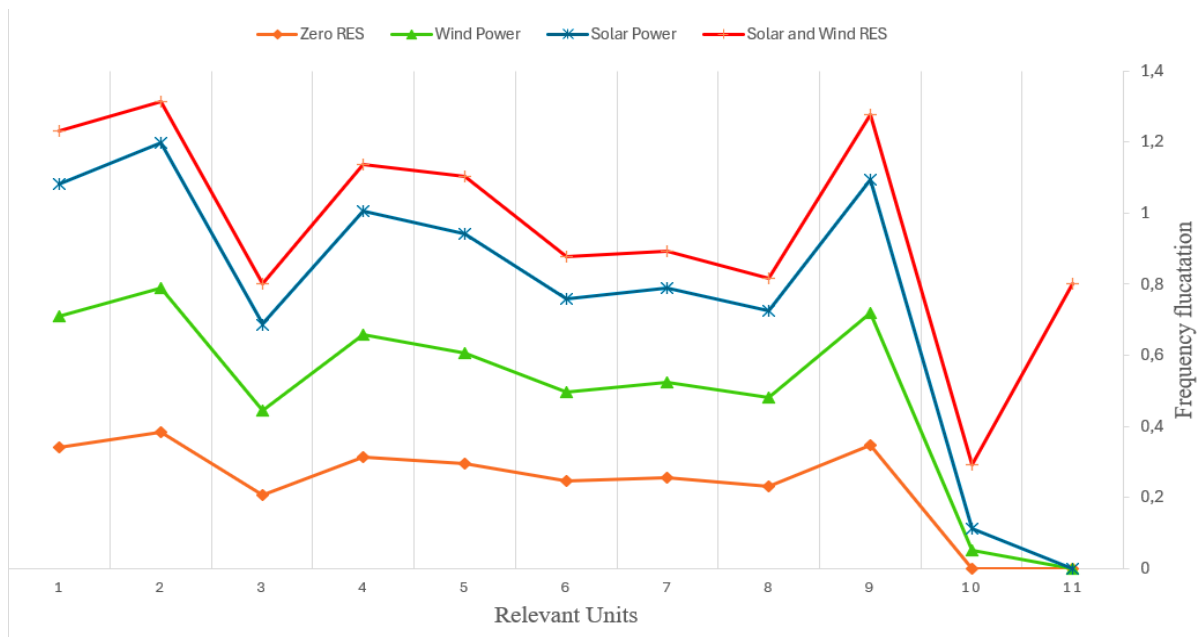


Figure 4.2. Frequency fluctuations for per RESs

In Figure 4.2 relevant units and their frequency fluctuation have been depicted by considering four various cases as mentioned above. The study's findings on the impact of wind power and photovoltaic (PV) energy on power system stability are summarized as follows:

➤ Improved Frequency Regulation Stability with Wind and Solar Energy:

It has been established using characteristic roots that incorporating wind and solar energy into the power system for frequency management results in better stability. This shows that incorporating these renewable energy sources improves the power system's dynamic response and stability.

➤ Improved Damping Properties in the Power System:

The investigation on the IEEE 39 bus power system demonstrates that the system's damping characteristics can be effectively improved. Wind-solar renewable energy integration into the power system helps to greater system stability. This discovery highlights the potential benefits of incorporating renewable energy sources into current power networks, particularly in terms of improving system stability.

➤ Increased Stability through Photovoltaic Power Stations.

In essence, the findings highlight the benefits of incorporating renewable energy sources, such as wind and solar, into the power grid. These findings are essential not only for addressing the increasing percentage of renewable energy in the power system but also for highlighting specific improvements in stability and damping characteristics related to the integration of these technologies.

4.2 Load frequency response

In order to demonstrate the aforementioned impact of wind power integration into a power system frequency, the MATLAB 2023b/Simulink model of the system is assembled according to the instructions provided in this section. The evaluation of a scenario is delineated as follows. The behavior of an individual region and its interaction between two interconnected areas are investigated in these scenarios. Generators in one area are uniform and consolidated into a singular entity. Wind power is only included in area 1, and the simulation involves a load disturbance that is simulated using a step function of 0.04 per unit. Area 1 is subjected to a load disturbance in order to assess the assistance offered by area two to area one. Wind penetration level is modified by altering the values of inertia reduction: 0%, 10%, 25%, 45%, and 60%. The impact of wind sources on Load Frequency Control (LFC) will be examined by doing a comparative analysis of scenarios, taking into account variations in frequency response and excluding any other factors and equivalent regulation constants. The research system's parameters are derived from reference [44] and are presented in Table 4.5. The parameters provided are standard values for a system and have been expressed into per unit and parameters of area two are obtained from reference [45] and can be seen in Table 4.6 in the Appendix. Area one is the only one that experiences the load disruption.

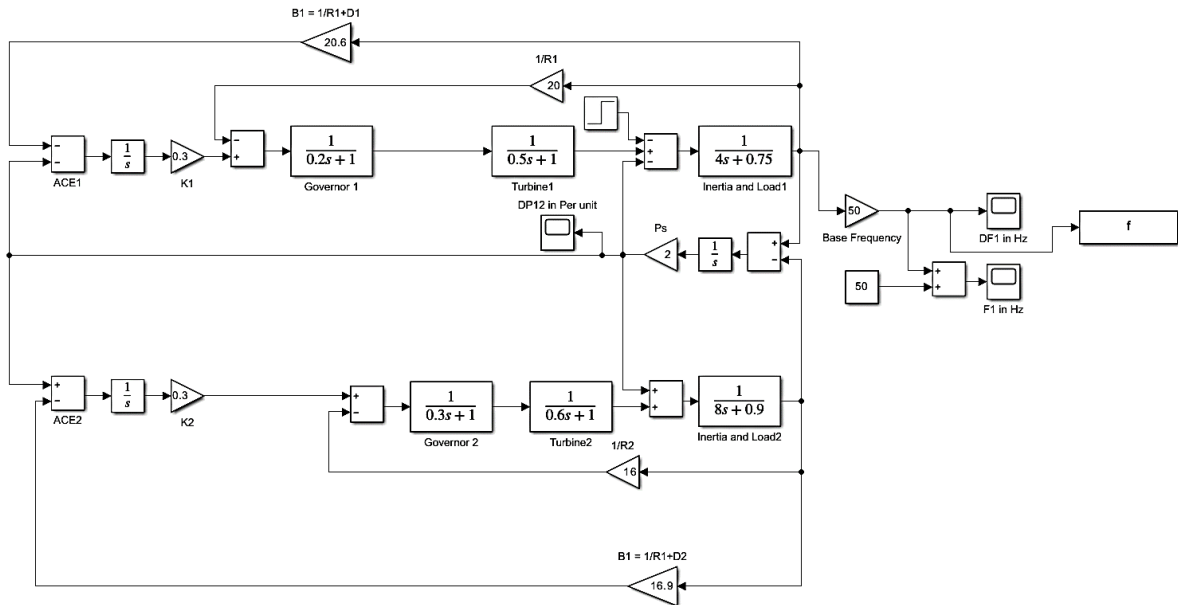


Figure 10. Load frequency response: Two-area connected system.

Table 4.4. RES penetration percent and parameters

Renewable penetration level(%)	K	D(pu/Hz)	2H	R(Hz/pu)	T _g (s)	T _t (s)
0	-0,3	0,015	10	3	0,2	0,5
10	-0,3	0,015	9	3,3	0,2	0,5
25	-0,3	0,015	7,5	3,75	0,2	0,5
45	-0,3	0,015	5,5	4,35	0,2	0,5
60	-0,3	0,015	4	4,8	0,2	0,5

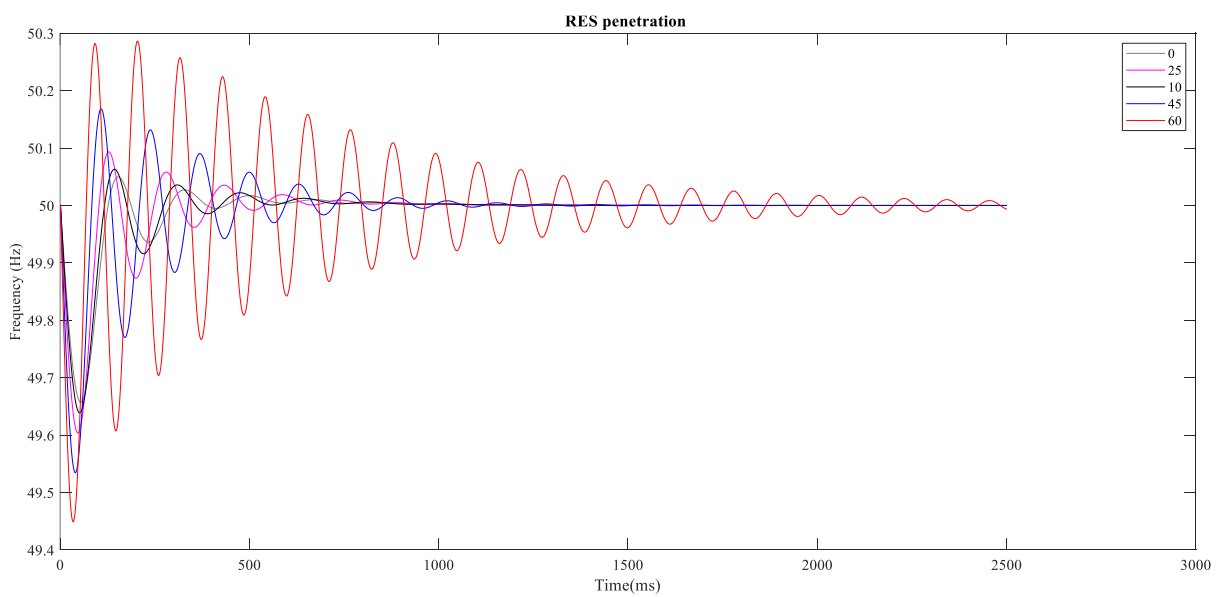


Figure 11. RESs penetration level and Frequency response

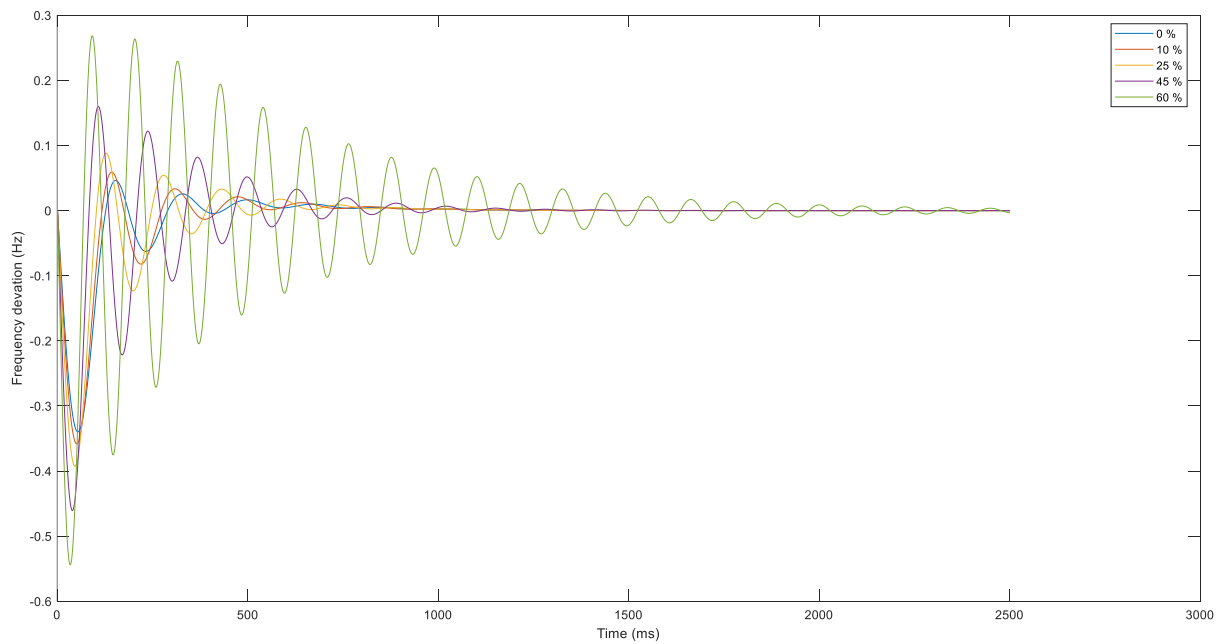


Figure 12. RESs penetration level and ROCOF

This simulation looks into how wind power affects load frequency control, with a focus on various penetration levels. As stated above, Figure 4.3 the mathematical model and simulation results highlight several important conclusions:

➤ **Decrease in Inertia of the System:**

The integration of wind power is linked to a decrease in the total inertia of the system. Inertia plays a crucial role in the electrical power system's stability and response to frequency variations. The system's capacity to withstand disruptions may be affected if its inertia decreases.

➤ **Variations in the Frequency Response Properties:**

The simulation's findings demonstrate how the integration of wind power affects the characteristics of frequency response. More specifically, the system's capacity to control and preserve frequency stability is impacted by a rise in the regulatory constant.

➤ **Impacts on Frequency Deviation:**

Increases in area control error, tie-line power flow, and frequency deviation are among the effects of integrating wind power. The behavior of the dynamic and performance of the power system under varying situations are crucially indicated by these characteristics.

➤ Examining Disregarded Factors:

The study emphasizes how load frequency control studies frequently ignore the reduction in system inertia and modifications in frequency response characteristics brought about by wind power. Understanding these elements in detail is necessary to fully comprehend the ways in which wind power integration influences system dynamics.

➤ Recommendations for Wind Power Levels:

Guidelines for determining the permissible amount of wind generation are provided by the analysis in Figure 4.4 and Figure 4.5. These regulations take into account the system's configuration, the maximum load disturbance, and the secure range of frequency excursions. Grid operators can use this information to decide how much wind power integration is appropriate while maintaining system stability.

➤ Importance for Grid Managers:

For grid operators, the findings in this research provide valuable information. By illuminating potential obstacles and constraints linked to shifts in system inertia and frequency response characteristics, this data might support decision-making processes pertaining to renewable energy sources integration.

In conclusion, simulation makes a significant contribution to our understanding of the sometimes-disregarded effects of RES integration on changes in frequency response characteristics and system inertia reduction. Grid operators can use the practical factors offered by the recommendations to make well-informed judgments about the degree of wind power integration that preserves system stability.

CHAPTER FIVE

CONCLUSION

This master's thesis thoroughly analyzes the complex interactions involved in integrating renewable energy, particularly wind and solar power, into the IEEE 39 bus power system. The methodology was run, developed, and assessed in MATLAB 2023b. It rigorously examines four different scenarios that represent various combinations of wind and solar energy integration. The study's key findings and contributions are as follows. Improved stability of frequency regulation with the integration of wind and solar energy: The examination of characteristic roots confirms that the integration of wind and solar energy greatly enhances the stability of the power system. This indicates an increased and more effective reaction and improved steadiness when using renewable energy sources.

➤ Enhanced Damping Characteristics in the Power System

The research reveals that the integration of wind and solar renewable energy significantly improves the damping qualities of the power system. The improvement in damping properties has significant consequences for the overall stability of the system. Empirical evidence demonstrates that the integration of photovoltaic power stations into the electricity grid effectively enhances system stability. This finding highlights the distinct advantages of integrating solar energy sources into the electricity grid. The investigation encompasses load frequency regulation, examining the consequences of integrating wind power at different levels of penetration. The simulation results provide significant insights:

➤ Decrease in System Inertia

The integration of wind power is associated with a noticeable decrease in the overall inertia of the system, which could have implications for stability.

➤ Changes in Frequency Response Characteristics

The incorporation of wind power causes noticeable alterations in the characteristics of frequency response, suggesting possible difficulties in maintaining and controlling frequency stability.

➤ Implications on Frequency Deviation:

The study reveals significant rises in area control error, and frequency deviation as outcomes of wind power integration. These findings highlight the intricate and complex behavior of the power system in different scenarios.

The research provides prescriptive recommendations for wind power levels, including criteria for estimating acceptable amounts of wind generation based on parameters such as frequency excursion, load disturbance, and system setup. The practical knowledge gained from this research provides a useful asset for grid operators, enabling them to make wise decisions on the level of wind power integration while maintaining system stability.

To summarize, this master's thesis provides scholarly perspectives on the complex dynamics of incorporating renewable energy into power systems. It emphasizes the need for careful examination of stability and control aspects throughout the continuous shift towards a sustainable and renewable energy-focused model.

APPENDIX

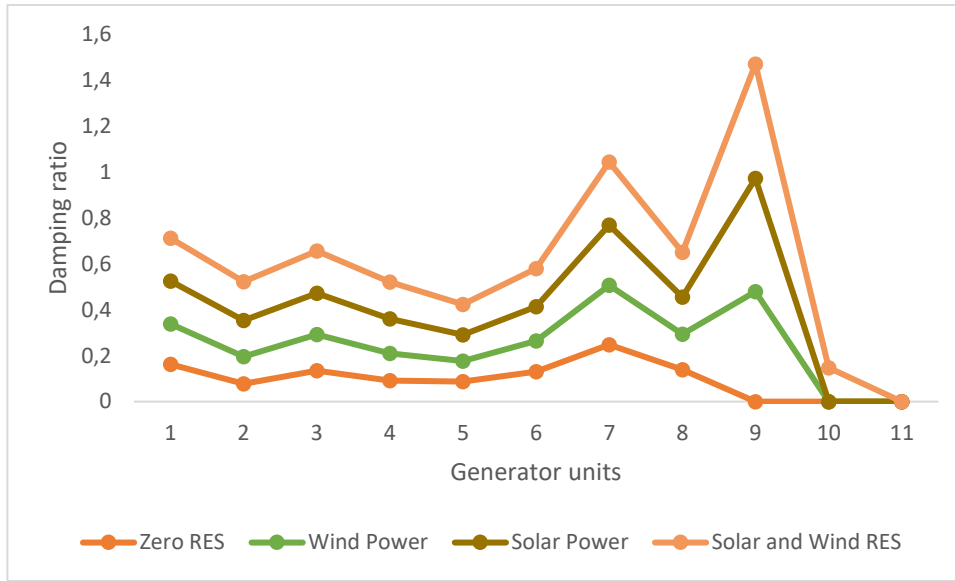


Figure 13 . Damping ratio for per RESs

Table 4.5. RES penetration percent and parameters-area two

Renewable penetration level (%)	K	D(pu/Hz)	2H	R(Hz/pu)	T_g(s)	T_t(s)
0	-0,3	0,018	8	3	0,3	0,6
10	-0,3	0,018	8	3	0,3	0,6
25	-0,3	0,018	8	3	0,3	0,6
45	-0,3	0,018	8	3	0,3	0,6
60	-0,3	0,018	8	3	0,3	0,6

REFERENCES

- [1] H. Holttinen, A. Tuohy, M. Milligan, E. Lannoye, V. Silva, S. Müller, L. S'õ, The flexibility workout: managing variable resources and assessing the need for power system modification, *IEEE Power Energy Mag.* 11 (2013) 53–62, <https://doi.org/10.1109/MPE.2013.2278000>.
- [2] J. Ma, V. Silva, R. Belhomme, D.S. Kirschen, L.F. Ochoa, Evaluating and planning flexibility in sustainable power systems, *Power and Energy Society General Meeting (PES), 2013 IEEE*, IEEE, <https://doi.org/10.1109/TSTE.2012.2212471>, 2013, 1-11-.
- [3] M. Alizadeh, M.P. Moghaddam, N. Amjady, P. Siano, M. Sheikh-El-Eslami, Flexibility in future power systems with high renewable penetration: a review, *Renew. Sustain. Energy Rev.* 57 (2016) 1186–1193, <https://doi.org/10.1016/j.rser.2015.12.200>.
- [4] N. Troy, E. Denny, M. O'Malley, Base-load cycling on a system with significant wind penetration. <https://doi.org/10.1109/TPWRS.2009.2037326>, 2019.
- [5] K. Van den Bergh, E. Delarue, Cycling of conventional power plants: technical limits and actual costs, *Energy Convers. Manag.* 97 (2020) 70–77, <https://doi.org/10.1016/j.enconman.2015.03.026>.
- [6] R.R. Londero, C. de Mattos Affonso, J.P.A. Vieira, Long-term voltage stability analysis of variable speed wind generators, *IEEE Trans. Power Syst.* 30 (2015) 439–447, <https://doi.org/10.1109/TPWRS.2014.2322258>.
- [7] L. Meegahapola, D. Flynn, in: *Impact on Transient and Frequency Stability for a Power System at Very High Wind Penetration*, Power and Energy Society General Meeting, 2010, pp. 1–8, <https://doi.org/10.1109/PES.2010.5589908>.
- [8] M. Edrah, K.L. Lo, O. Anaya-Lara, Impacts of high penetration of DFIG wind turbines on rotor angle stability of power systems, *IEEE Transactions on Sustainable Energy* 6 (2015) 759–766, <https://doi.org/10.1109/TSTE.2015.2412176>.
- [9] Department of Energy (DoE), *Integrated Resource Plan Update: Assumptions, Base Case Results and Observations (Revision 1)*, vol. 583, no. 40445. 2016, pp. 15–207.
- [10] M. L. Coker and G. A. Chown, "Eskom Under-Frequency Load Shedding Scheme Re-Design Simulation Studies."
- [11] S. Homan, N. M. Dowell, S. Brown, "Grid frequency volatility in future low inertia scenarios: Challenges and mitigation options," *Appl. Energy.*, vol. 290, pp. 116723, Mar. 2021.
- [12] H. B. Yang, et al., "Virtual inertia control strategies for double-stage photovoltaic power generation," *Automation of Electric Power Systems.*, vol. 656, no. 10, pp. 132-147, May. 2019. (in Chinese)
- [13] O. Gandhi, et al., "Review of power system impacts at high PV penetration Part II: Factors limiting PV penetration," *Sol Energy.*, vol.210, pp. 202-221, Aug. 2020
- [14] G. Shrimali and E. Baker, "Optimal feed-in tariff schedules," *IEEE Trans.Eng. Manag.*, vol. 59, no. 2, pp. 310_322, May 2012.
- [15] G.Wang, V. Kekatos, A. J. Conejo, and G. B. Giannakis, "Ergodic energy management leveraging resource variability in distribution grids," *IEEE Trans. Power Syst.*, vol. 31, no. 6, pp. 4765_4775, Nov. 2016.
- [16] G. Liu, "Generation scheduling for power systems with demand response and high penetration of wind energy," Ph.D. dissertation, Univ. Tennessee, Knoxville, TN, USA, 2014.
- [17] K. Nghitevelekwa and R. C. Bansal, "A review of generation dispatch with large-scale Photovoltaic (PV) systems," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 615_624, Jan. 2018.
- [18] Karel Máslo, "Effects of Renewable Energy on Frequency Stability: A Proposed Case Study of the Kenyan Grid," pp 3648-3655, Vol.31, No. 5, September 2016
- [19] Alqahtani, S.; Shaher, A.; Garada, A.; Cipcigan, L. Impact of the High Penetration of Renewable Energy Sources on the Frequency Stability of the Saudi Grid. *Electronics* **2023**, *12*, 1470. <https://doi.org/10.3390/electronics12061470>

- [20] Tan, J.; Zhang, Y.; You, S.; Liu, Y.; Liu, Y.; Frequency Response Study of U.S. Western Interconnection under Extra-High Photovoltaic Generation Penetrations. In Proceedings of the IEEE Power and Energy Society General Meeting, Portland, OR, USA, 5–10 August 2018; pp. 1–5.
- [21] Feilat, E.; Azzam, S.; Al-Salaymeh, A. Impact of large PV and wind power plants on voltage and frequency stability of Jordan's national grid. *Sustain. Cities Soc.* **2018**, *36*, 257–271.
- [22] National Renewable Energy Program. Saudi Arabia Renewable Energy Targets and Long-Term Visibility. 2018. Available online: <https://www.powersaudi Arabia.com.sa/web/attach/media/Saudi-Arabia-Renewable-Energy-Targets-and-Long-Term-Visibility.pdf> (accessed on 9 June 2022).
- [23] Electricity and Cogeneration Regulatory Authority. Electricity Generation Stations Capacities. 2017. Available online: www.ecra.gov.sa (accessed on 6 June 2022).
- [24] Al-Mohaisen, A.I. Electricity Network Connectivity between the GCC Countries; GCC Interconnection Authority: Dammam, Saudi Arabia, 2011; pp. 1–31.
- [25] Saudi Electricity Company. System Operation & Control Procedures; Saudi Electricity Company: Riyadh, Saudi Arabia, 2022.
- [26] Alturki, Y.A.; Edris, A.-A. Saudi Arabia's Growing Demand for Electricity: Some Strategic Recommendations. *J. Energy Power Eng.* **2015**, *9*, 296–302.
- [27] M. Dreidy, H. Mokhlis, and S. Mekhilef, "Inertia response and frequency control techniques for renewable energy sources: A review," *Renewable and Sustainable Energy Reviews*, vol. 69, no. November 2015, pp. 144–155, 2017.
- [28] Lam, K. H., Lai, T. M., Lo, W. C., & To, W. M. (2012). The application of dynamic modelling techniques to the grid-connected PV (photovoltaic) systems. *Energy*, 46(1), 264-274. <https://doi.org/10.1016/j.energy.2012.08.023>
- [29] F. F. Bai, X. R. Wang, Y. L. Liu, X. Y. Liu, Y. Xiang, and Y. Liu, "Measurement-based frequency dynamic response estimation using geometric template matching and recurrent artificial neural network," *CSEE Journal of Power and Energy Systems*, vol. 2, no. 3, pp. 10–18, Sep. 2016.
- [30] A. Gloe, C. Jauch, B. Craciun, and J. Winkelmann, "Continuous provision of synthetic inertia with wind turbines: Implications for the wind turbine and for the grid," *IET Renew. Power Gener.*, vol. 13, no. 5, pp. 668_675, Apr. 2019.
- [31] M. J. P. Jaghargh and H. R. Mashhadi, "Structural and behavioral evaluation of renewable energy power plants' impacts on transmission network congestion using an analytical approach," *IET Renew. Power Gener.*, vol. 14, no. 7, pp. 1164_1173, Apr. 2020.
- [32] P. Bhatt, R. Roy, and S. P. Ghoshal, "Dynamic contribution of DFIG along with SMES for load frequency control of interconnected restructured power system," in *Proc. 10th Int. Conf. Environ. Elect. Eng. (EEEIC)*, 2011, pp. 1–5.
- [33] C. Kang, L. Yao, "Key scientific issues and theoretical research framework for power systems with high proportion of renewable energy," *Automation of Electric Power Systems*, vol. 41, no. 9, pp. 2-11, 2017.
- [34] P. Liao, X. Li, "A Survey on Calculation Methods of Wind Power Penetration Limit," *Power System Technology*, vol. 32, no. 10, pp. 50-53, 2008.
- [35] KUNDER P, "Power system stability and control," New York, USA: McGraw-Hill, pp. 377-460, 1994.
- [36] D. Wilson, J. Yu, N. Al-Ashwal, et al, "Measuring effective area inertia to determine fast-acting frequency response requirements," *International Journal of Electrical Power & Energy Systems*, vol. 113, pp. 1-8, 2019.
- [37] M. Tavakoli, M. Power, L. Ruttledge, et al, "Load Inertia Estimation Using White and Grey-Box Estimators for Power Systems with High Wind Penetration," *IFAC Proceedings Volumes*, vol. 45, pp. 399-404, 2012.
- [38] H. Holttinen and J. Pedersen, "The effect of large-scale wind power on a thermal system operation," in *Proc. 4th INT. Works Large-Scale Integer*.
- [39] Wind Power Transmiss. Netw. Offshore Wind Farms, 2003, pp. 20_22.

- [40] D. Parra, S. A. Norman, G. S. Walker, and M. Gillott, "Optimum community energy storage for renewable energy and demand load management," *Appl. Energy*, vol. 200, pp. 358–369, Aug. 2017.
- [41] Y. Zhang, Y. Xu, H. Guo, X. Zhang, C. Guo, and H. Chen, "A hybrid energy storage system with the optimized operating strategy for mitigating wind power fluctuations," *Renew. Energy*, vol. 125, pp. 121–132, Sep. 2018.
- [42] X. Xi, H. Geng, and G. Yang, "Enhanced model of the doubly fed induction generator-based wind farm for small-signal stability studies of weak power system," *IET Renewable Power Generation*, vol. 8, no. 7, pp. 765–774, 2014.
- [43] K. V. Vidyanandan and N. Senroy, "Primary frequency regulation by deloaded wind turbines using variable droop," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 837–846, 2013.
- [44] H. Bevrani, *Robust Power System Frequency Control*. New York, NY, USA: Springer, 2009.
- [45] K. P. S. Parmar, S. Majhi, and D. P. Kothari, "Optimal load frequency control of an interconnected power system," *MIT Int. J. Elect. Instrum. Eng.*, vol. 1, no. 1, pp. 1–5, Jan. 2021.