

To the Graduate Council:

I am submitting herewith a thesis written by Mishal Hajaj Alonize entitled “Assessment of Wind Power Integration into the Synthetic Electric Grid of Saudi Arabia.” I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Electrical Engineering.

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Dr. Fangxing Li, Major Professor

We have read this thesis  
and recommend its acceptance:

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Dr. Hantao Cui

Accepted for the Council:

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Dixie L. Thompson

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(Original signatures are on file with official student records.)

# **Assessment of Wind Power Integration into the Synthetic Electric Grid of Saudi Arabia**

A Dissertation Presented for the  
Doctor of Philosophy  
Degree  
The University of Tennessee, Knoxville

Mishal Hajaj Alonize

December 2025

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# Dedications

*I would like to dedicate this dissertation to my beloved parents, my lovely wife, and my children.*

# Acknowledgements

All thanks to Allah for His immense blessings, for granting me the strength and determination to finish this work.

I would like to express my heartfelt thanks to Dr. Fangxing Li for his constant support, patience, and valuable guidance throughout my Ph.D. journey. His feedback, suggestions, and ideas have been critical in improving my research. I am truly grateful for the opportunity to work with such an inspiring mentor and thank him for everything.

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# Abstract

Saudi Arabia is working to reduce its dependence on oil and diversify its economy by incorporating renewable energy into its plans, as part of the initiative Vision 2030. A significant challenge in this change is the integration of renewable energy, particularly wind energy, into the existing Saudi Arabian electricity grid.

Wind energy offers significant economic and environmental benefits, including reducing carbon emissions and providing a cost-effective energy source. However, integrating wind power presents challenges, particularly in maintaining grid frequency stability during different disturbances and ensuring that wind farms comply with grid codes to operate efficiently within the system.

To perform tests for the effectiveness of wind integration, an adaptive synthetic Saudi electric grid model was built based on data of the Saudi power grid collected from open source data, designed to simulate the transient dynamics of a Saudi power grid, in order to enable simulation and assessment of wind energy integration into the electricity system of Saudi Arabia. For higher accuracy and details, the model created by CURENT Large-scale Testbed (LTB) and its ANDES package.

Regarding wind energy, data on wind resources in Saudi Arabia support the conclusion that many areas of the Kingdom are ideal for the installation of wind farms. As a result, future wind resources have been designed to assess and comply with regulations of the grid code. They also address the specific operational challenges associated with wind farms and the addition of solar photovoltaic (PV) power. Then, it examines how the high penetration of wind power affects the frequency stability of Saudi synthetic electric grids by evaluating how the system performs for several penetration levels in different regions when different disturbances are applied.

Finally, the dissertation evaluates potential mitigation strategies to enhance grid stability, with a focus on integrating battery energy storage systems (BESS) and adjusting control synchronous machines. Thus, the results of this dissertation provide initial insight into the future integration of wind energy into the Saudi electric grid.

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# Nomenclature

|                 |                                                     |
|-----------------|-----------------------------------------------------|
| <i>BESS</i>     | Battery Energy Storage systems                      |
| <i>COR</i>      | Central Operating Region                            |
| <i>DG</i>       | Distributed Generation                              |
| <i>EOR</i>      | Eastern Operating Region                            |
| <i>GASTA</i>    | General Authority for Statistics                    |
| <i>HVDC</i>     | High Voltage Direct Current                         |
| <i>IEA</i>      | International Energy Agency                         |
| <i>IRENA</i>    | International Renewable Energy Agency               |
| <i>K.A.CARE</i> | King Abdullah City for Renewable Energy             |
| <i>KAPSARC</i>  | King Abdullah Petroleum Studies and Research Center |
| <i>LTB</i>      | CURRENT Large-scale Testbed                         |
| <i>NERC</i>     | North American Electric Reliability Corporation     |

|              |                                        |
|--------------|----------------------------------------|
| <i>NERP</i>  | National Renewable Energy Program      |
| <i>NOR</i>   | Northern Operating Region              |
| <i>POC</i>   | Point of Connection                    |
| <i>PSSE</i>  | Power System Simulator for Engineering |
| <i>ROCOF</i> | Rate of Change of Frequency            |
| <i>SAGC</i>  | Saudi Arabian Grid Code                |
| <i>SEC</i>   | Saudi Electric Company                 |
| <i>SOR</i>   | Southern Operating Region              |
| <i>SSEG</i>  | Saudi Synthetic Electric Grid          |
| <i>UFLS</i>  | Under Frequency Load Shedding          |
| <i>WOR</i>   | Western Operating Region               |
| <i>WTG</i>   | Wind Turbine Generator                 |

# Chapter 1

## INTRODUCTION

### 1.1 Background

The Saudi Arabian goal is to enhance the prospective future of the country through sustainability-based planning, infrastructure development, and investment. An essential aim of Saudi Vision 2030, announced in April 2016, is to reduce dependence on oil. One of the vision targets is to generate significant renewable energy to achieve this goal (4). In addition, the King Salman Renewable Energy project will support the second stage and private sector investment in generation energy projects with the manufacturing industry. Saudi Arabia plans to establish 9.5 gigawatts of wind and solar power capacity under this projects established (5).

Although early goals focused on solar power, Saudi Arabia has increasingly recognized the potential of wind power as an important component of its energy. The Saudi Arabian renewable energy strategy has expanded to include wind energy projects, which offer many

economic and environmental benefits (6). Wind energy can significantly reduce carbon emissions and mitigate the effects of global warming while serving as a cost-effective energy source (7; 8).

Recent developments have indicated an increase in wind energy initiatives. In January 2019, the Saudi Ministry of Energy launched its first wind energy auction as part of its National Renewable Energy Program. A prominent project under this initiative is the Dumat Al Jandal wind farm, a 400 MW facility that began operating in 2021 and represents a major milestone in the Saudi Arabian renewable energy journey. Developed by a consortium led by EDF Renewables and Masdar, the project is the largest wind farm in the Middle East. The wind farm will provide clean energy to approximately 70,000 households, making a significant contribution to the goals of Saudi Arabia's renewable energy. By 2030, the Kingdom will aim to diversify its energy and has set ambitious goals to integrate wind power into its electricity grid (9; 6).

Wind power projects not only contribute to diversifying the energy combine, but also play a significant role in job creation and technology transfer. The participation of international companies in these projects promotes knowledge exchange and the development of local expertise in renewable energy technologies (9). In addition, wind power is economically useful in the long term, especially considering the savings resulting from the reduction of fossil fuel consumption and environmental conservation efforts (10).

## 1.2 Motivation

As mentioned in the previous section, the Saudi Arabian government is working on a major transformation in its effort to reduce dependence on oil and natural gas as the main sources of electricity generation, by selecting sustainable renewable energy as one of the pillars of its economic and environmental future. Among these efforts, wind power is one of the main sources that can play an essential role in generating electricity in the Kingdom, particularly in areas with promising wind conditions.

Wind energy is one of the effective solutions to address the challenges associated with fluctuations in global oil prices and trends toward reducing carbon emissions. The Kingdom, which has huge areas with different natural resources, including strong winds in some areas such as the northwest, has come to see wind energy as a strategic opportunity to enhance energy stability and reliance on different sources.

However, the Kingdom faces challenges similar to those faced with solar power. Despite the availability of the natural resources necessary to generate wind power, there has been no long research history or wide experience in integrating this technology into the electrical infrastructure country. Therefore, an analysis of how the integration of wind power affects the stability of the Saudi electrical grid is required.

It is well known that integrating large numbers of wind power turbines into the grid can affect frequency stability due to this interrupted and unstable nature of this source, particularly those sudden changes in drops or sudden increases in the power grid. For



this reason, detailed studies should be conducted to understand and evaluate the potential impacts on the Saudi national grid as the dependence on wind power increases.

Although a comprehensive dynamic model of the Saudi electrical grid is not publicly available for research and studies, a Saudi synthetic electric grid is needed designed to simulate the transient dynamics of an actual power grid. This synthetic grid model needs to be built using open source data based on accurate data collected from the available public database, is available for open sharing, and can be used for educational and research purposes. Through the CURENT large-scale testbed (LTB) and the special package set for testing, tuning, and validation, it is designed to fit a detailed model of the elements of the Saudi power system, the requirements of the Saudi code, and the statistical characteristics found in real power grids.

## 1.3 Contribution

The contributions of this dissertation are as follows.

- Creating an open-source, accurate model that represents the dynamic behavior of the Saudi synthetic electric grid to scientific participation for academic and research communities.
- Design and implementation of Saudi synthetic electric grid using the advanced tools CURENT Large-scale Testbed (LTB) to represent study statistics simulation, dynamic simulation, and grid visualization.

- Validating the dynamic stability of the Saudi synthetic electric grid by simulating various disturbances, such as generator trips, load shedding, and line disconnections, at different points within the grid.
- Representing a simulation of one of the future wind turbine farm projects in Saudi Arabia to evaluate technical and operational obstacles associated with integrating wind power into the existing Saudi power grid infrastructure.
- Investigate the ability of wind farms to remain operational and maintain grid stability during transient faults or disturbances in the power system.
- Analyze and review the simulation results to make sure that adding wind farms does not affect the security and reliability of the Saudi power grid. Also, check if it meets the rules and standards of the Saudi Arabian electricity grid.
- Comparison of LVRT requirements across different grid codes to discover differences in terminology, thresholds, testing procedures, and other technical specifications.
- Creating and developing a synthetic model of the high-wind penetration scenarios model for educational and training purposes that accurately simulates real-world scenarios.
- Technical visualization and evaluation of the expected future requirements and functions for integrating wind energy into the Saudi power grid.

## 1.4 Dissertation Organization

This section contains an overview of each chapter.

- **Chapter 2:** The chapter on the review of the literature presents a comprehensive analysis of the integration of wind power into existing power infrastructures, with particular emphasis on the technological advancements, opportunities, and challenges that are essential for this transition. It begins by investigating the global and regional context, emphasizing the rapid development of wind energy and the unique challenges faced in Saudi Arabia, including grid stability and intermittency (Part One). The discussion then illustrates the motivation behind the research, with a particular emphasis on the role of technological advancements, such as modern wind turbine innovations, in addressing these challenges (Part Two). The third part of the chapter explores Saudi Arabia's wind energy initiatives, including case studies such as the NEOM wind farm, and identifies frequency regulation as a critical issue that requires comprehensive solutions. In the final section, it assesses wind turbine technologies and solutions, including battery energy storage systems and synthetic inertia, which present optimistic approaches to improving grid performance and mitigating frequency instability (Part Four).
- **Chapter 3:** This chapter creates and develops a synthetic model of the Saudi power grid, with the aim of simulating its dynamic behavior while adhering to Saudi code requirements in the real world. The model, built using the CURENT Large-scale Testbed (LTB) platform, replicates the geographic, load, and generation profiles of the

Saudi grid. By simulating various disturbances, the model is validated for dynamic stability, confirming its reliability for real-world applications. A synthetic case study of 224 buses that demonstrates the ability to capture the complex details of the Saudi electrical grid, including transient behaviors and geographic resolution. This open source model serves as a base for researchers and educators to explore the dynamics of the power system and expand into wide areas of power system research.

- **Chapter 4:** This chapter is about integrating wind power into the Saudi Arabian electricity grid. Focuses on model design for future wind resources and compliance with grid codes. Examines the specific operational challenges associated with wind farms and when adding solar PV. The chapter assesses how well wind farms can remain stable when there are disturbances in the grid. The second part focuses on the grid rules that allow large-scale integration of renewable energy. In addition, Comparative analyses of worldwide practices on compliance with LVRT requirements.
- **Chapter 5:** This chapter examines how the high penetration of wind power affects the frequency stability of Saudi synthetic electric grids by evaluating how the system performs for several penetration levels (20%, 40%, 60%, and 75%) in different regions. The upcoming chapters elaborate on wind farms of possible future sites, evaluating the same with a variety of frameworks including impact from a conventional generation trip in each region impact on frequency metrics penetration on under-frequency load shedding impact from installed full wind penetration in one region.

- **Chapter 6:** This chapter aims to discuss potential mitigation measures and control strategies to enhance frequency regulation in SSEG. Integration of battery energy storage systems (BESS). In addition, increasing the number of generators with active governors are evaluated to maintain grid stability during these events in the SSEG stability. The measures and proposed solutions provided here are intended to better evaluate and manage the effects of renewable integration on grid stability.

# Chapter 2

## LITERATURE REVIEW

### 2.1 Challenges and Opportunities of Wind Power Integration

The integration of wind power into current electricity grids presents a difficult challenge, which requires a review of technological, economic, and regulatory considerations (11; 12). Wind energy is one of the fastest growing renewable energy sources worldwide, accounting for 24% of the renewable electricity results in 2023, as reported by the International Energy Agency (IEA) (13). However, issues such as variability, grid stability, and frequency regulation remain significant challenges (14). In Saudi Arabia, where the power grid is mainly dependent on fossil fuels, the integration of fluctuating wind power requires the creation of grid management strategies (1; 15; 16). Thus, integrating wind energy has potential and challenges due to Saudi Arabia relying on centralized power generation, especially when it

comes to preserving the frequency and stability of the system during power fluctuations. In summary, the effects of wind power on the electricity system are largely influenced by the following factors.

- The extent of wind power integration
- The size of the grid.
- The variety of electricity generation sources within the system.

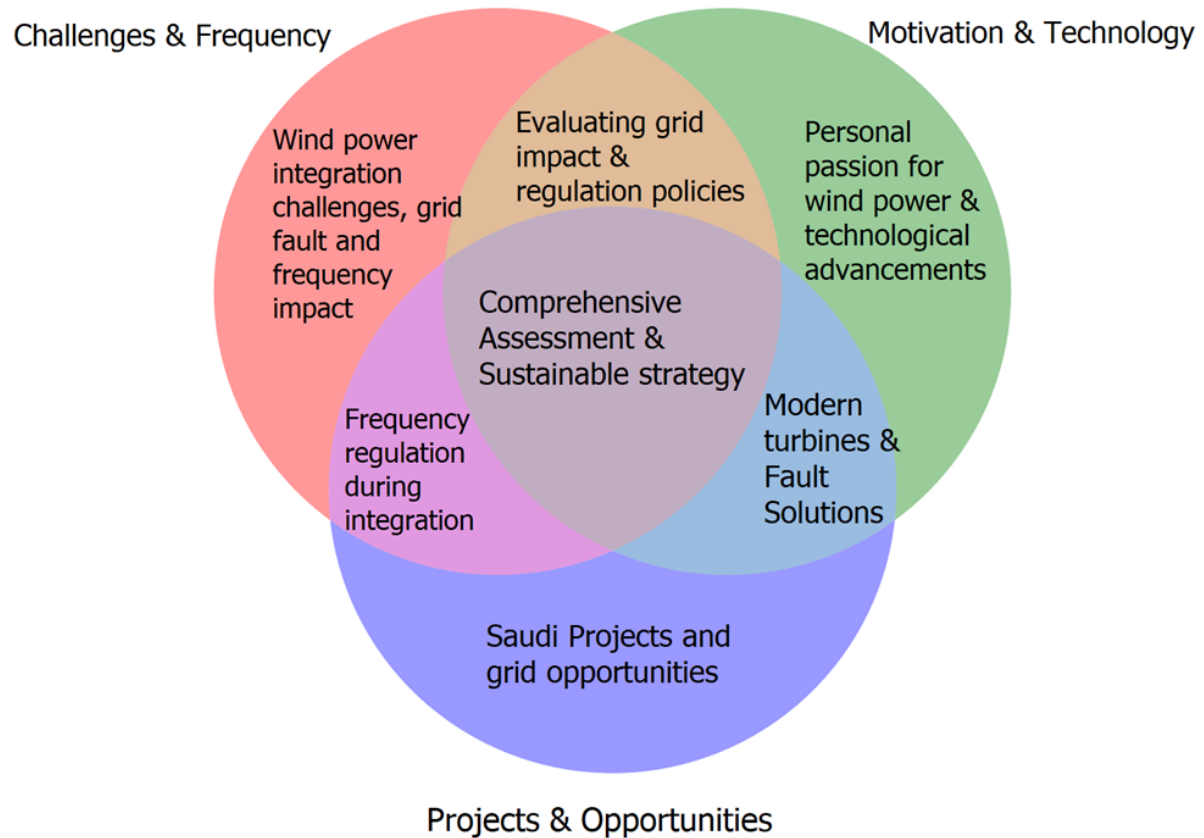
In Saudi Arabian, the integration of wind power into the grid could have a significant impact. Vision 2030 has committed to renewable energy, targeting 50% the generation of electricity from renewable energy sources by 2030. The 400 MW Dumat Al Jandal wind farm project is promising (4; 9; 6). The integration of wind power changes the frequency of the grid in the event of a fault. Many faults have also been noted. The Saudi Electricity Company reported a power outage that occurred in the city of Sharurah on Friday 12 July 2024 (17). In June 2019, an event occurred in which a transmission line fault occurred in the southern region, causing a drop in frequency of 1.2 Hz (18). The resolution of these issues requires the support of technologies consisting of energy storage, smart grid, and mitigation solutions (19; 20; 21).

## 2.2 Motivation for Research and Role of Technological Advancements

The motivation to assess the integration of wind power into the Saudi system comes from both personal and academic interests, as well as future wind projects. This research, based on renewable energy and grid systems, background, and motivated by a dedication to sustainable energy, aims to address significant issues in the transition to energy in Saudi Arabian. Furthermore, the idea of the dissertation is described in the summary shown in Figure 2.1. Evaluating the grid for the integration of wind energy is essential to ensure reliability, stability, and efficiency. In addition, grid frequency control is essential to preventing faults, an issue that is increased by the interrupted nature of wind power. These challenges underscore the importance of evaluation and strategic planning.

Modern wind turbine technology has transformed the renewable energy market and provided solutions to the challenges of frequency regulation (22). Technological advances including doubly fed induction generators (DFIGs), permanent magnet synchronous generators (PMSGs) and advanced grid compatible inverters facilitate turbine active participation in grid frequency control (23; 24; 25). A study by She, Buxin et al. (2023) highlights how synthetic inertia provided by modern wind turbines can mitigate frequency drops during grid faults (26). In Saudi Arabia, integrating this technology into new wind projects ensures that the grid can handle the variability of wind energy while maintaining operational stability.





**Figure 2.1:** The diagram summarizes the interconnected themes within the areas of the dissertation

## 2.3 Saudi Arabian Wind Power Projects and Frequency Challenges

Saudi Arabia has made significant progress in the development of wind power, with projects such as the Dumat Al Jandal wind farm serving as a regional milestone. This 400 MW project offsets approximately 988,000 tons of CO<sub>2</sub> per year, according to the Saudi Energy Efficiency Center (6). Future projects in Neom and Al Jouf aim to harness the high wind speeds prevalent in the northwestern regions (5; 27; 28). However, the integration of these projects into the grid poses challenges related to frequency stability, particularly during faults. For example, the 2021 blackout in the western region, caused by a transformer failure, caused a frequency drop of 0.8 Hz, disrupting the power supply of 1.2 million households (1).

Regulation and technology must be used in combination to address frequency stability issues. To prevent frequency decreases, Saudi Arabian grid operators advise using fast response systems and battery energy storage systems (BESS) (29). Therefore, setting grid rules that require frequency support capabilities for wind farms is absolutely essential. Putting emphasis on the need for grid code compliance to ensure steady integration of wind energy, a 2022 report by the International Renewable Energy Agency (IRENA) states that these measures can greatly improve grid performance in concert with predictive analytics and real-time monitoring (30).

## 2.4 Modern Wind Turbines and Solutions for Frequency Regulation

Modern wind turbines play a critical role in maintaining the frequency of the grid, particularly during faults (31; 32) . Technologies such as high-speed communication protocols, grid-friendly inverters and the integration of energy storage allow turbines to provide synthetic inertia and reactive power support (19; 33; 34). A notable development is the use of DFIGs, which allow flexible operation and active frequency regulation. Research by Marco et al. (2023) demonstrated that wind turbines equipped with advanced controllers reduced frequency drops during simulated fault conditions (35). Several wind turbine manufacturers around the world have begun to adopt these technologies, ensuring compliance with the requirements of the national grid.

To address frequency regulation challenges, several methods have been proposed and implemented globally. These include fast-frequency response systems, BESS and hybrid energy storage solutions (36; 37; 38). In 2021, the North American Electric Reliability Corporation (NERC) reported that combining wind farms with BESS reduced frequency recovery time (39). For Saudi Arabia, incorporating such solutions into wind power projects not only mitigates frequency instability but also enhances grid resilience. Collaborative efforts between grid operators, policymakers, and technology providers are essential to realize these advances. Using modern wind turbine technology and adopting comprehensive frequency regulation strategies, a comprehensive study is required to assess the future performance of wind power farms in the Saudi electricity grid.

Recent studies have extensively examined the integration of renewable energy, particularly wind energy, into synthetic electric grids. The study by Alqahtani et al. (2023) (Impact of the High Penetration of Renewable Energy Sources on the Frequency Stability of the Saudi Grid) examines how increasing amounts of renewable energy affect the frequency stability of the Saudi grid (40). It focuses on the issues that arise with the dynamics and stability of the grid when there are many renewable energy sources. However, it does not address the synthetic modeling of the Saudi power grid. This means that it limits its scope to grid performance rather than flexible testing environments during the real grid.

The study "Frequency Stability in Renewable-Rich Modern Power Systems: Saudi Grid Case Study" by Alqahtani et al. (2022) provides an analysis of the frequency stability challenges posed by the integration of renewable energy sources into the Saudi power grid (41). The research highlights the dynamic interactions between renewable generation and the existing grid infrastructure. However, the study does not focus primarily on the Saudi grid in detail, limiting its ability to explore hypothetical scenarios and custom configurations that could better represent future grid expansions or variations. Although the study offers valuable information on the technical challenges of renewable integration, it does not investigate the specific contributions or limitations of wind energy penetration. This leaves a gap in understanding the unique impact of wind energy in a synthetic model that mirrors the Saudi grid.

In contrast, there are currently no studies that specifically assess the penetration of wind energy into a Saudi synthetic power grid in detail. This gap provides a potential opportunity for future research to develop and analyze customized synthetic models, which will provide a more comprehensive assessment of the potential role of wind power and its implications for the stability, reliability, and performance of the developing energy infrastructure in the Saudi Arabian grid.

## Chapter 3

# MODELING AND VALIDATING SYSTEM DYNAMICS IN SAUDI SYNTHETIC ELECTRIC GRID

### 3.1 Overview

As mentioned earlier, a synthetic grid is needed to implement research on electrical power systems in Saudi Arabian grid systems. This chapter presents a modeling approach for constructing a synthetic Saudi electric grid, which accurately simulates the transient behavior of a real-world power grid. Using open-source data, the synthetic grid model has been meticulously developed and is openly available for educational, training, and research purposes. The model is designed to reflect the detailed characteristics of the Saudi

power system, including compliance with Saudi code requirements and statistical properties simulated in actual power grids using the CURENT Large-scale Testbed (LTB) platform.

## 3.2 Saudi Power Grid System Description

The Saudi power system is growing and becoming more complex to manage, experiencing grid challenges and the need for economic efficiency and stability that utilities all over the world have (42). In 2022, the electricity generation from Saudi power plants was 359,637 gigawatt hours (GWh). The current power generation infrastructure includes a range of units, ranging from small 15 megawatt (MW) installations to large and modern 720 megawatt units, with a total actual network installed capacity of 83,539 MW. The maximum load on the grid reached 65,301 MW in 2022, and the customer base exceeded 10.9 million, with more than 398 thousand new customers acquired over the year (1). The available electric capacity amounted to 83,036 MW in 2021 with an increase of 4.23%, compared to 2020. The peak load also increased by 3.04% reaching 64,161 MW in 2021. By 2030, the energy-generating capacity of the Saudi power system is projected to increase to 120 GW. As a result, the Saudi government intends to expand its sources of power generation and improve the efficiency of the current grid. Hence, the current grid needs to have sufficient strength and resilience to meet the expected future improvements, such as the integration of renewable energy sources and the implementation of interconnections with neighboring countries. This expansion is intended to meet the substantial increase in expected power consumption (43).

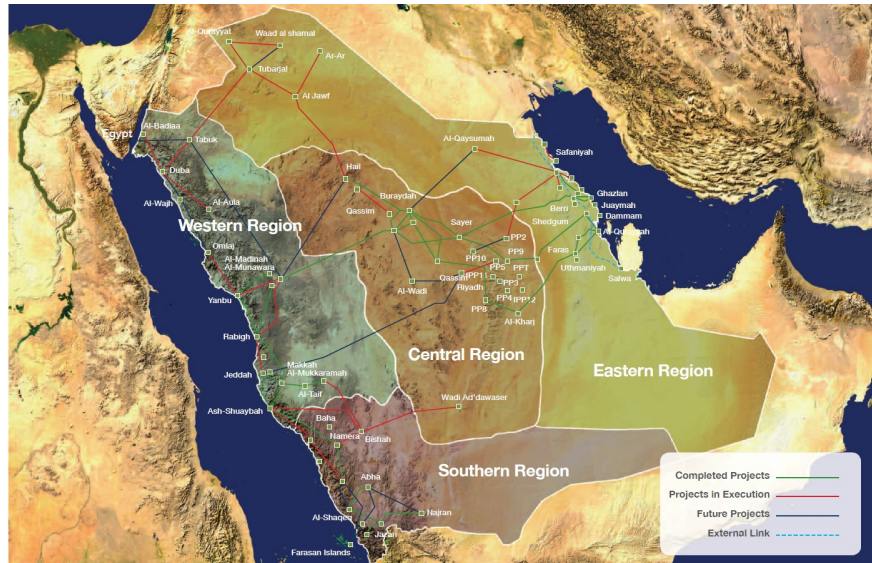
### 3.2.1 Saudi Arabian Electric Grid Operating Regions, Voltage Level and Fuel Types

The electrical system in Saudi Arabia is strategically divided into four primary operational regions that correspond to the geographical regions of the Kingdom: the Western Operating Region (WOR), the Eastern Operating Region (EOR), the Central Operating Region (COR) and the Southern Operating Region (SOR) (1). The (WOR) is of significance because of its high population density. The EOR, which includes the oil-rich regions of the Kingdom, plays an important role due to its close proximity to major industrial centers and the Persian Gulf. The COR, with its center in the capital Riyadh, serves as the administrative center of the grid. However, the Southern Operating Region , which covers less heavily populated regions, prioritizes providing reliable energy to isolated and rural towns. while the (SOR), which covers less densely populated areas, focuses on providing reliable electricity to remote and rural communities. The Northern Operating Region (NOR) of the Saudi Arabian power grid currently has significant interconnection projects aimed at improving grid reliability and efficiency (1).

Furthermore, the standard voltage levels of the Saudi electrical grid range from 380 to 13.8 kV (1). It contains an advanced electricity transmission grid with different transmission lines with different voltage levels. Each features specific voltage levels and transmission line grids tailored to meet the region's power demands and geographic characteristics. In the (WOR) and (COR), a high voltage level of 380 kV is used, reflecting the need for reliable power transmission to support the large electrical load in these regions. In addition, the



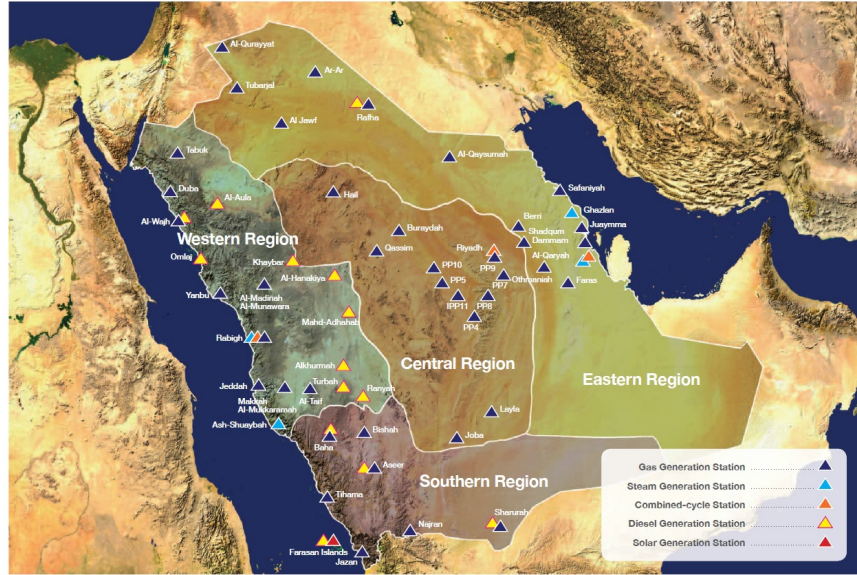
110 kV voltage level is commonly used to facilitate the distribution of electricity within regions. In the (EOR), 230 kV transmission lines are used, especially due to its proximity to the country's oil fields and industrial areas. In addition, in some regions of the EOR, the voltage levels are 115 kV to meet the industrial demand of the oil and gas sector. The SOR contains 132 kV. These transmission lines are common mainly in remote and rural areas, with 132 kV conductors to ensure that remote communities can access electricity (44). The 13.8 kV voltage level is also used in the Saudi electricity grid, mainly for the distribution of medium voltage within regions. It is a standard voltage for distributing power from distribution substations to local transformers, which then reduce the voltage for smaller residential, commercial, and industrial consumers. Figure 3.1 shows the transmission lines in the current and future Saudi electric grid. The Saudi synthetic electric grid model will be designed based on this diagram (44).



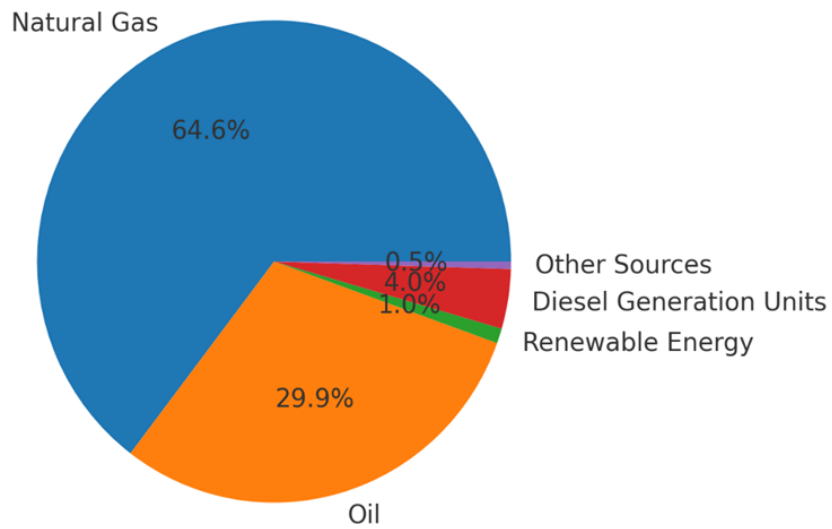
**Figure 3.1:** Current and future transmission lines in the Saudi power grid (1)

As Figure 3.2 shows, Saudi Arabia relies on oil and natural gas to generate electricity due to the abundant reserves of these resources. The grid consists of 477 electric power generation units located in 46 power plants distributed across different regions. Figure 3.3 illustrates the primary fuel types used for electricity generation in 2022. Natural gas is the popular energy source, reaching approximately 64.7% of the total electricity produced in the country. Oil, which also contributes substantially, is responsible for 29.9% of electrical generation. Diesel production units constitute a small part, accounting for 4%, of power generation. They are used primarily to supply electricity in remote areas where other sources of energy are less accessible (1). In recent years, Saudi Arabia has made significant investments in renewable energy projects, especially solar and wind power, to reduce its dependence on fossil fuels for energy. One of the most renewable energy projects in Saudi Arabia is the development of the King Salman Renewable Energy Initiative, which aims to generate 50% of the energy from renewable sources by 2030. This initiative includes the construction of large-scale solar power plants, wind farms, and other renewable energy installations across the country (5).

As part of this transition, Saudi Arabia has begun several programs to increase the share of renewable energy in its energy. These include large-scale projects to use solar and wind power. In particular, wind turbines are a good choice because the country has high wind conditions in most regions, which will be discussed in Chapter 5. These projects not only help reduce carbon emissions, but also help diversify the energy sources. This makes the electric grid more stable and less dependent on fluctuation in the oil and gas markets (4; 5).



**Figure 3.2:** Types and places of power plant generation in the Saudi power grid (1)



**Figure 3.3:** Primary Fuel Types Used for Electricity Generation in Saudi Arabia (1)

### 3.2.2 Saudi Arabian Grid Code Requirements

The main objective of a grid code requirement is to prevent detrimental impacts on the operation, reliability, and power quality of the system (45). Regarding the performance of transmission systems, the Saudi Arabian Grid Code (SAGC) demonstrates a high level of congruence with IEEE 1547 (46). Including the grid code and implementing it in practice is what ensures the stability, security, and efficient operation of the electrical grid system (29). To enhance the efficiency of the transmission system, electrical parameters should remain within acceptable limits, as suggested by the SAGC guidelines. The following parameters are described below.

- **Frequency Variations:** The standard frequency of the transmission system is 60 Hz and must be kept within the range of 59.9 to 60.1 Hz under regular operating conditions. The design of the generating system and the auxiliary control equipment should be within the limits specified in Table 3.1.
- **Voltage Variations:** The specified nominal voltage transmission range values, as presented in Table 3.2, should be within. In rare situations, the maximum over voltage limits must not be exceeded for a duration longer than 30 minutes.

**Table 3.1:** Frequency operation requirement as per Saudi Arabian grid code.

| Below Nominal Frequency (Hz) | Above Nominal Frequency (Hz) | Operation Requirements. |
|------------------------------|------------------------------|-------------------------|
| 58.8 — 60.0                  | 60.0 — 60.5                  | Continuous              |
| 57.5 — 58.7                  | 60.6 — 61.5                  | For a period of 30 min  |
| 57.0 — 57.4                  | 61.6 — 62.5                  | For a period of 30 sec  |

**Table 3.2:** Nominal Voltage and Range Specifications

| Nominal Voltage Range (KV) | Normal Range | 30-Minute Range |
|----------------------------|--------------|-----------------|
| 110 kV                     | $\pm 5\%$    | $\pm 10\%$      |
| 115 kV                     | $\pm 5\%$    | $\pm 10\%$      |
| 132 kV                     | $\pm 5\%$    | $\pm 10\%$      |
| 230 kV                     | $\pm 5\%$    | $\pm 10\%$      |
| 380 kV                     | $\pm 5\%$    | $\pm 10\%$      |

By integrating these codes into the SSEG model, it can accurately simulate the behavior of the grid under different conditions and assess its performance in maintaining the stability and reliability required during SAGC. In addition, the SAGC serves as a crucial reference in the construction of a reliable and efficient SSEG model, ensuring that all electrical parameters in the model are maintained within acceptable limits, as outlined in the grid codes.

### 3.2.3 Model Selection and Evaluation

According to statistics, all generation machines in the Saudi power system are thermal units (15). Therefore, the process of building a synthetic grid emphasizes modeling generators, which constitute the predominant portion of the overall installed generation capacity. Additionally, lower-order dynamic models and a lower level of complexity are chosen through the LTB ANDES packages (47).

#### 1) Synchronous Generators:

- **Machine:** In (48), it is established that the GENROU machine model applies primarily to thermal units. Consequently, the GENROU model is the dominant machine model in the synthetic grid, assigned to all generators.

- **Governor:** according governors are highly dependent on fuel types, steam turbines and gas turbines have been chosen for the steam governor model (TGOV1) and the gas governor model (GAST) (48).
- **Exciter:** In the Siemens PTI PSS®E library, there are 38 exciter models are adopted for natural gas power plants. However, a simplified excitation system (SEXS model) will be applied to the excitation systems within each machine in the SSEG (48).

## 2) Load:

- **Load:** The general load demand information in each city is collected from the Saudi Arabian General Authority for Statistics (GASTAT). Both public and private electricity demand is highly correlated with population, as determined using geographic coordinates in a statistical analysis of the electrical energy consumed by the residential sector in different regions (15). However, there is a lack of detailed dynamic load information, particularly regarding how load types such as constant power, constant current, and constant impedance loads interact with the grid voltage under different conditions. This gap in dynamic load data can cause challenges in the behavior of the power system model under faults and disturbances (49).

To address this limitation, a simplified static P-Q load model has been used, which provides an approximate representation of the impact of the load on the stability of the system. In this model, the active power (P) and the reactive power (Q) demands of the system are assumed to be constant (50). Specifically, the active power load is considered as a 100% constant current load, while the reactive power load is considered a 100% constant admittance load.

### 3) **Transmission Line:**

- **Transmission Line:** The substations are connected using synthetic transmission line configurations at different specified voltage levels, as noted in reference (51). Most of the Saudi transmission line system is in the form of overhead lines. As a result, synthetic lines are configured with parameters similar to those of overhead lines, as mentioned in the reference (52). The transmission line configuration is developed using Google Maps. For the purpose of AC power flow analysis, the essential electrical parameters for transmission lines encompass series impedance, shunt admittance, and megavolt-ampere (MVA) limits. Line length (L) is determined by the straight-line distance between the geographic coordinates of the designated substations. Furthermore, the initial transmission lines parameters like resistance, reactance, substances are used by manufacturing parameters according to the many factors like line length, weir type, and number of boundless.

## 3.3 Simulation Results and Validation of the Synthetic grid Model

### 3.3.1 CURENT Large-scale Testbed (LTB)

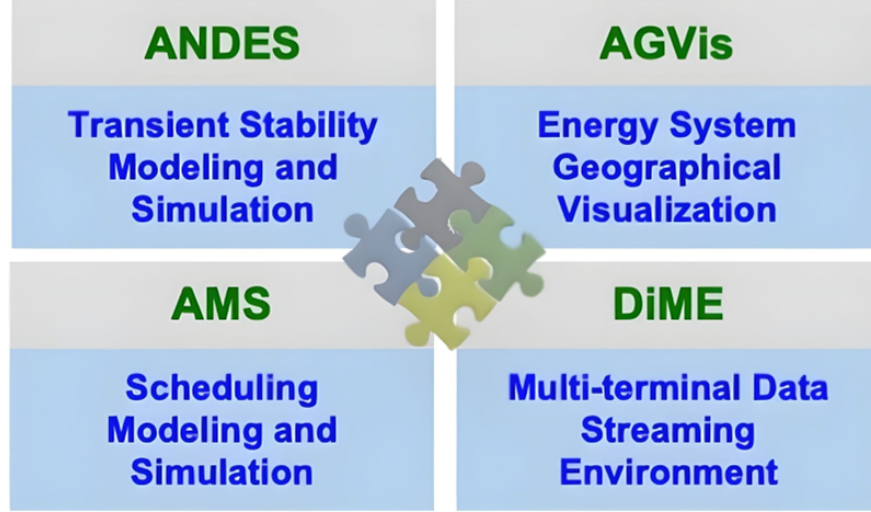
Power grids are being updated to achieve the highest level of reliability, efficiency, and cost effectiveness through the integration of renewable energy, large-scale monitoring, and advanced control technology. This complexity requires a rapid modeling platform for research and testing in new transmission technologies (53). Commercial software simulations often lack the integrated and closed-loop capabilities required for such real-time testing (54).

Therefore, a fully automated, integrated, and closed-loop platform with detailed system modeling is ideal as a virtual digital double of an actual power grid for research and the study of power systems. This approach allows research on power system monitoring, modeling, control and operation to be conducted in an integrated closed-loop environment, offering high accuracy and flexibility in modeling (53).

The CURENT Large-Scale Test Bed (LTB) facilitates prototyping and simulation of the power system as a large-scale digital twin. LTB platform includes four core packages, ANDES, AMS, AGVis, and DiME. These packages provide dynamic simulation, market simulation, geographic visualization, and a data messaging environment, respectively (2). As in Figure 3.4 demonstrated an overview of the Large-scale Testbed architecture and components. These packages can be used independently for specific research purposes or in conjunction with closed-loop studies. To simplify the process for use, LTB provides a



repository that includes all four packages as submodules (55; 2). Additionally, ANDES offers a comprehensive set of commercial-grade dynamic models, complete with detailed implementations, including limiters, saturation, and zeroing of time constants. (56).



**Figure 3.4:** Demonstrated overview of the (LTB) architecture and components (2)

CURRENT LTB serves as a comprehensive platform for simulating and analyzing the dynamic behavior of power systems. LTB was developed to model synthetic networks such as the Saudi power grid and integrate components such as the ANDES package to perform power flow studies, transient stability, and small signal stability simulations. In addition, AGVis provides network visualization capabilities, enhancing real-time situational awareness. The Saudi synthetic grid model, consisting of 224 buses, was built, validated, and tested using LTB features, ensuring a practical and accurate analysis for research and educational purposes. In (8) the LTB platform workflow has been represented. Figure 3.5 shows the SSEG representing the Saudi power system. This synthetic grid has been generated using ANDES and is represented by AGVis, which provides grid element data sets in different

formats. In addition, there is a flow chart for the steps that describe the construction of SSEG, where this project task is divided into three basic steps, as shown in Figure 3.6.

### 3.3.2 Power Flow Results

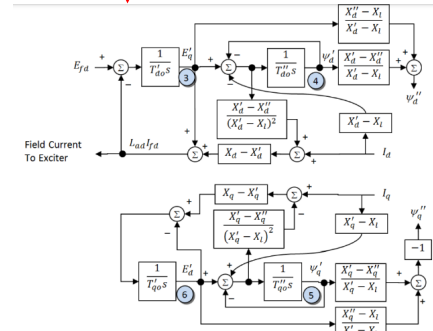
During the statistics and open data, steady-state data, such as active power and load demand in each city, were provided. In contrast, the reactive power of each bus was estimated because the data was not provided since it was assumed that all buses had a power factor of 0.95. The Saudi synthetic power grid consists of 224 buses with voltage levels ranging from 380 to 13.8 kV. Using ANDES , the power flow simulation is conducted using the Newton-Raphson method with four iterations for the base operating conditions, making sure that the voltage magnitudes are within 0.95 - 1.05 p.u. as the standards imposed by the SAGC. Table 3.3 shows the composition of the Saudi synthetic power system model.

**Table 3.3:** Composition of synthetic Saudi power system model.

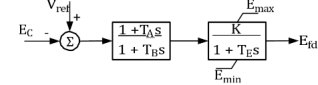
| Region | Region Code | Number of Buses | Number of Power Plants |
|--------|-------------|-----------------|------------------------|
| COR    | 300         | 52              | 15                     |
| EOR    | 200         | 40              | 14                     |
| WOR    | 100         | 66              | 19                     |
| NOR    | 500         | 38              | 9                      |
| SOR    | 400         | 28              | 11                     |



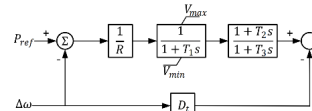
|        |                   |               |             |                           |             |              | Length |         |         |       |       |  |
|--------|-------------------|---------------|-------------|---------------------------|-------------|--------------|--------|---------|---------|-------|-------|--|
| 500 kV | Name of Conductor | No of bundles | MVA         | Positive Sequence (pu/km) |             |              | 380kV  | 602     | 0.00516 | 0.061 | 6.791 |  |
|        |                   |               |             | R                         | X           | B            |        |         |         |       |       |  |
|        | Stranded          | 4             | MVA         | 0.0000958                 | 0.000109    | 0.0106066    |        |         |         |       |       |  |
|        | Arvidal           | 3             | 2072        | 0.000011446               | 0.000110241 | 0.01013494   |        |         |         |       |       |  |
|        | Drake             | 3             | 2679        | 0.000011905               | 0.000110952 | 0.010114762  |        |         |         |       |       |  |
| AAAC   | 4                 | 2772          | 0.00008571  | 0.000101429               | 0.011280714 |              |        |         |         |       |       |  |
| AAC    | 3                 | 2094          | 0.000010903 | 0.00011028                | 0.01066573  |              |        |         |         |       |       |  |
| ACCR   | 4                 | 2793          | 0.00008421  | 0.000100702               | 0.011319754 |              |        |         |         |       |       |  |
| 230 kV | Name of Conductor | No of bundles | MVA         | Positive Sequence (pu/km) |             |              | 230kV  | 414     | 0.0322  | 0.244 | 0.796 |  |
|        |                   |               |             | R                         | X           | B            |        |         |         |       |       |  |
|        | ACSS              | 2             | 674         | 0.000077778               | 0.000588889 | 0.001922222  |        |         |         |       |       |  |
|        | Rail              | 1             | 337         | 0.000151852               | 0.000801704 | 0.001426286  |        |         |         |       |       |  |
|        | ACCC              | 2             | 614         | 0.00008741                | 0.000605108 | 0.00188318   |        |         |         |       |       |  |
| Solid  | 1                 | 314           | 0.00016667  | 0.000813333               | 0.001375    |              |        |         |         |       |       |  |
| 132 kV | Name of Conductor | Tower Type    | MVA         | Positive Sequence (pu/km) |             |              | 110kV  | 169     | 0.1859  | 0.393 | 0.083 |  |
|        |                   |               |             | R                         | X           | B            |        |         |         |       |       |  |
|        | ACCR              | TBA           | 117         | 0.001005714               | 0.00235714  | 0.00048571   |        |         |         |       |       |  |
|        | ACSS              | D-8           | 182         | 0.000418518               | 0.00219259  | 0.000522222  |        |         |         |       |       |  |
|        | Cairo             |               | 118         | 0.0010189                 | 0.00242702  | 0.000497297  |        |         |         |       |       |  |
|        | GREELEY           | ZM-DST        | 184         | 0.00048888                | 0.0022222   | 0.00052222   |        |         |         |       |       |  |
|        | ACSS/TW           | ZM-DST        | 112         | 0.0011                    | 0.00232325  | 0.0004888872 |        |         |         |       |       |  |
|        | AAAC/TW           | TBA           | 112         | 0.001125                  | 0.002375    | 0.0005       |        |         |         |       |       |  |
|        | ACAR              | D-6           | 112         | 0.0011                    | 0.00228     | 0.0005       |        |         |         |       |       |  |
|        | ACSR/SD           | S-3           | 112         | 0.0011                    | 0.0023333   | 0.000483333  |        |         |         |       |       |  |
|        | AAC               | ZM-DST        | 202         | 0.00042857                | 0.00218571  | 0.000528571  |        |         |         |       |       |  |
| ZIGOLO | D-4               | 114           | 0.0010387   | 0.002303225               | 0.000496774 | 132kV        | 320    | 0.13714 | 0.699   | 0.169 |       |  |



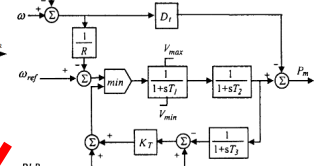
Block diagram for GENROU model



Block diagram for the SEXS model



Block diagram for the TGOV1 model



Block diagram for the GAST model

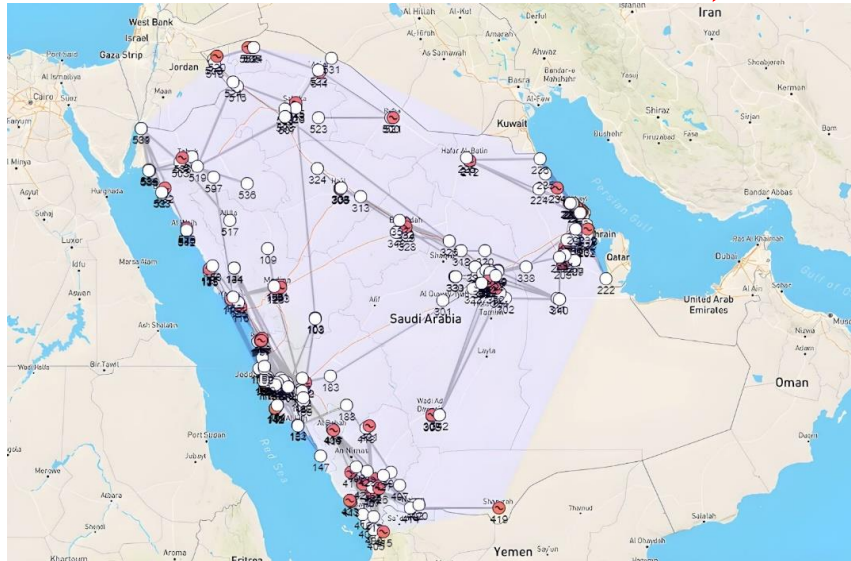
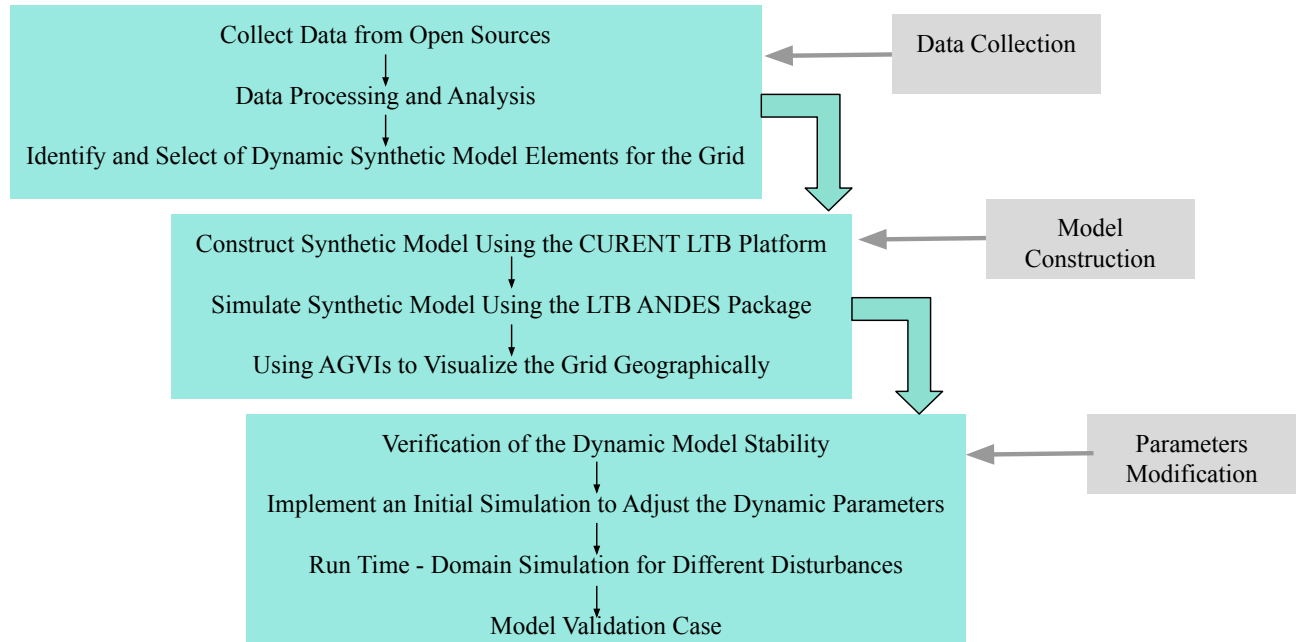


Figure 3.5: Detailed construction for synthetic grid representing the Saudi electric system by AGVis



**Figure 3.6:** Flow Chart for Synthetic Power System Model of Saudi Electric Grid

In the SSEG, the aggregate generation capacity of units belonging to the same type is combined and represented by one unit. QURAYA bus (202) in the EOR is chosen as the SWING BUS because it has the largest generation capacity. The aggregate active and reactive power generation amounts to 64,637 MW and 19,087 MVar, respectively, while the active and reactive power demands stand at 64,033 MW and 14,569 MVar, respectively. Tables 3.4 and 3.5 provide a comprehensive overview of the power flow results and the power flow of the operational regions.

**Table 3.4:** A comprehensive power flow result.

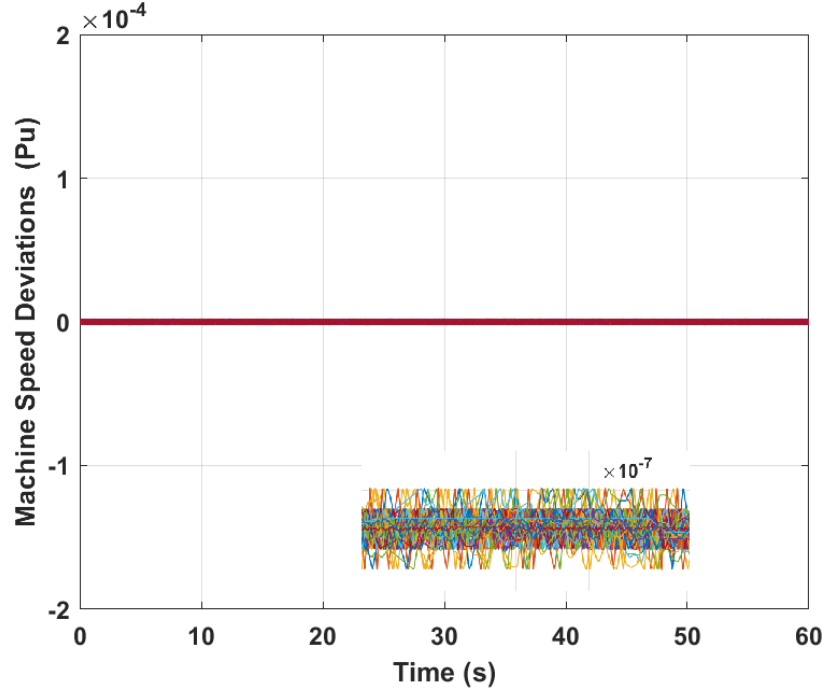
| <b>Parameter</b>                       | <b>Value</b>    |
|----------------------------------------|-----------------|
| Voltage limits [p.u.]                  | 0.953 to 1.0450 |
| Total active power generation [MW]     | 64,637          |
| Total reactive power generation [MVar] | 19,087          |
| Total active power load [MW]           | 64,033          |
| Total reactive power load [MVar]       | 14,569          |

**Table 3.5:** A comprehensive of the operational regions power flow data.

| <b>Region</b> | <b>Region Code</b> | <b>Generation [MW]</b>   |
|---------------|--------------------|--------------------------|
| COR           | 300                | 17,761.6                 |
| EOR           | 200                | 22,027.2                 |
| WOR           | 100                | 17,805.0                 |
| NOR           | 500                | 3,430.4                  |
| SOR           | 400                | 3,613.5                  |
| <b>Region</b> | <b>Region Code</b> | <b>Generation [MVar]</b> |
| COR           | 300                | 5,936.7                  |
| EOR           | 200                | 6,343.7                  |
| WOR           | 100                | 4,812.2                  |
| NOR           | 500                | 947.7                    |
| SOR           | 400                | 1,047.6                  |
| <b>Region</b> | <b>Region Code</b> | <b>Load [MW]</b>         |
| COR           | 300                | 18,471.8                 |
| EOR           | 200                | 20,673.8                 |
| WOR           | 100                | 17,531.7                 |
| NOR           | 500                | 3,323.7                  |
| SOR           | 400                | 4,032.3                  |
| <b>Region</b> | <b>Region Code</b> | <b>Load [MVar]</b>       |
| COR           | 300                | 4,399.6                  |
| EOR           | 200                | 4,768.8                  |
| WOR           | 100                | 3,822.4                  |
| NOR           | 500                | 767.4                    |
| SOR           | 400                | 809.9                    |

### 3.3.3 Flat Run Simulation Results

This disturbance-free 'flat run' simulation is carried out to verify that the dynamic models generate minimal or no transients. NERC suggests that simulations should ideally run for a minimum of 20 seconds to effectively detect any possible small signal or control-related instabilities that might arise within this time frame, as mentioned in reference (57). In the framework of the SSEG, a simulation without disturbances is conducted, with a duration of 60 seconds. The speed deviation of the machines in the model, frequency deviation and bus voltage deviations were measured, and the results are shown in Figure 3.7, Figure 3.8, and Figure 3.9, respectively. No deviation is observed in these results. Thus, this result shows that this model exhibits dynamic stability in the absence of any disturbances.



**Figure 3.7:** Machine speed deviation for all SSEG model machines

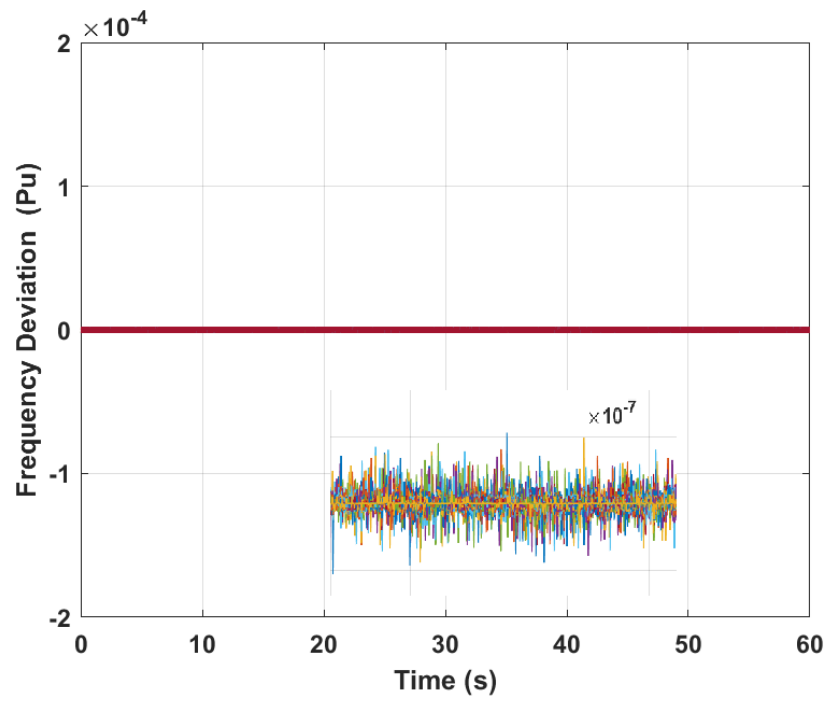


Figure 3.8: Frequency deviation for all SSEG model Buses

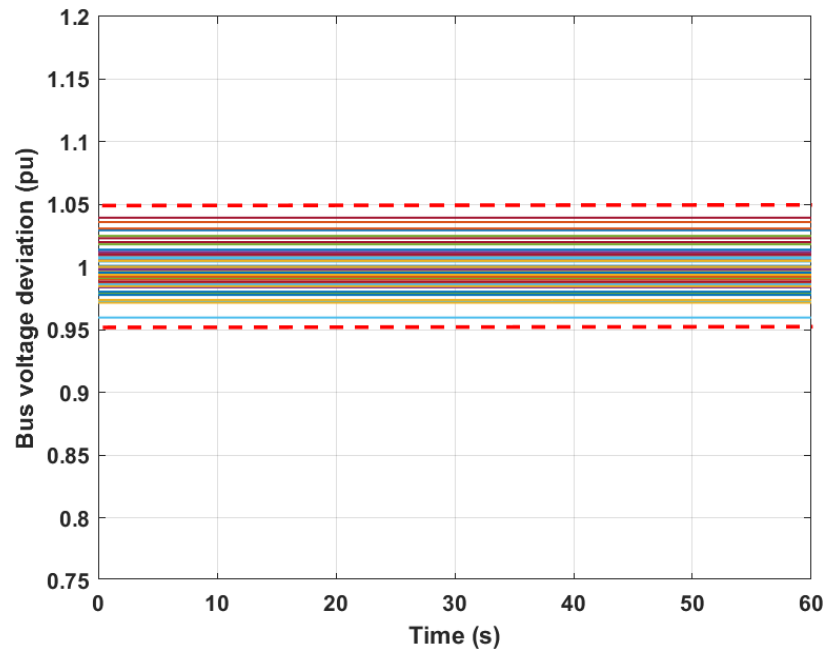
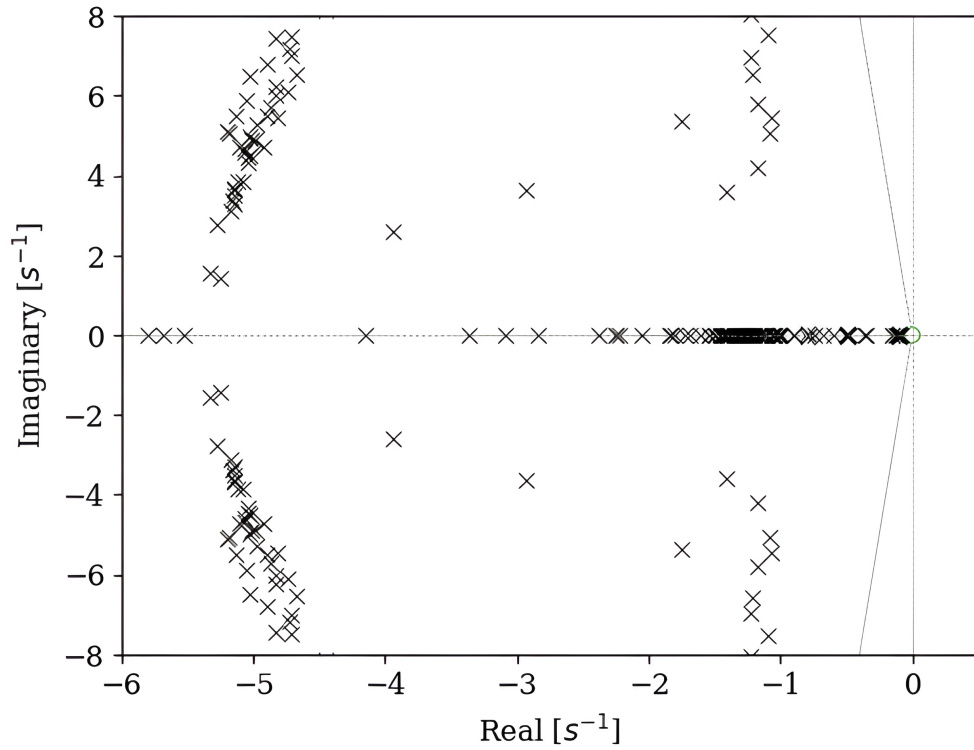


Figure 3.9: Bus voltage deviation for all SSEG model Buses



In the study of the SSEG model, eigenvalue analysis in ANDES provides insight into the stability of the system. Observing the real and imaginary components of the eigenvalues, this analysis identifies the stability and oscillatory behavior within the system, which are critical for control and dynamical system assessments. Stability is typically associated with eigenvalues that have negative real parts, as they indicate damping of disturbances over time. The plot shows that most of the eigenvalues have negative real parts, suggesting that the system is stable. As Figure 3.10 shows, most of the eigenvalues to the left of the complex plane confirm the general stability of the system.



**Figure 3.10:** Eigenvalue trajectory of the SSEG model

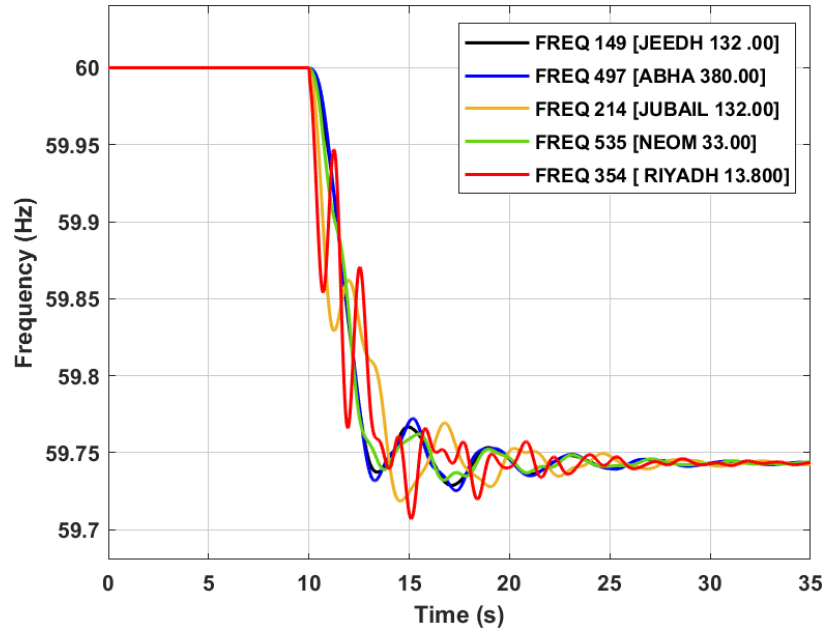
### 3.3.4 Dynamic Performance Analysis

Accurate analysis of events in the synthetic power system grid is essential to ensure situational validation, conformity to code requirements, and verification of grid behavior. Validate the dynamic stability of the synthetic Saudi grid model. It has been applied with an initial testing simulation and several time-domain simulations of different disturbances at different locations in the SSEG.

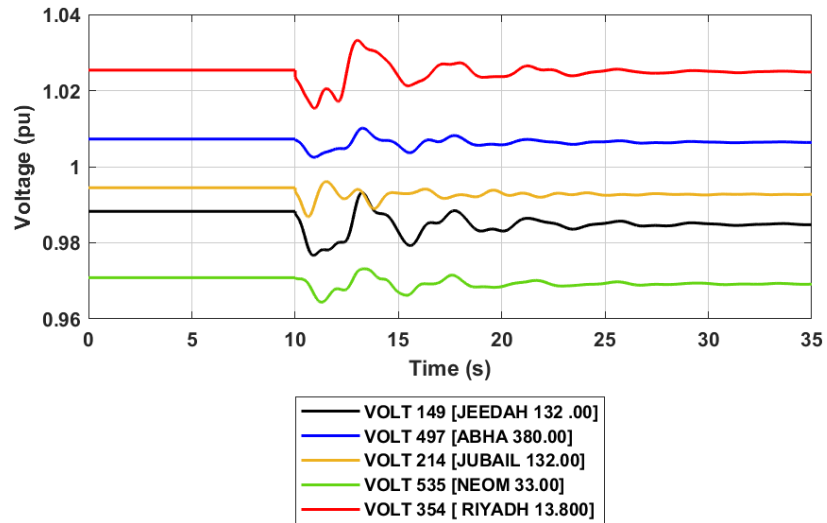
#### Generator Tripping Scenarios

##### 1) First Case :

In the COR region in the Riyadh city, a generator at bus 352 in PPT10 power plant station was tripped. The unit generating capacity is 1,965 MW. Figure 3.11 shows the system frequency response 10 seconds after this gas turbine unit in the five operating regions that represent the frequency response of the entire region COR (RIYADH bus), EOR (JUBAIL bus), WOR (JEDDAH bus), SOR (ABHA bus) and NOR (NEOM bus). Since the RIYADH bus (354) is very close to the tripped machine bus, its frequency took slightly more time to damp than the other two frequency responses. The frequency drop occurs because of an imbalance between generation and demand. By comparison. The NEOM bus in the northern region is very far from the tripped machine bus, so its frequency did not affect much. In the same case, Figure 3.12 shows that the voltage magnitude on the RIYADH bus (354) fluctuated slightly between 1.0330 and 1.0153 per unit, with little effect in the other regions.



**Figure 3.11:** System frequency response after generator trip at bus 352 in the Central region.

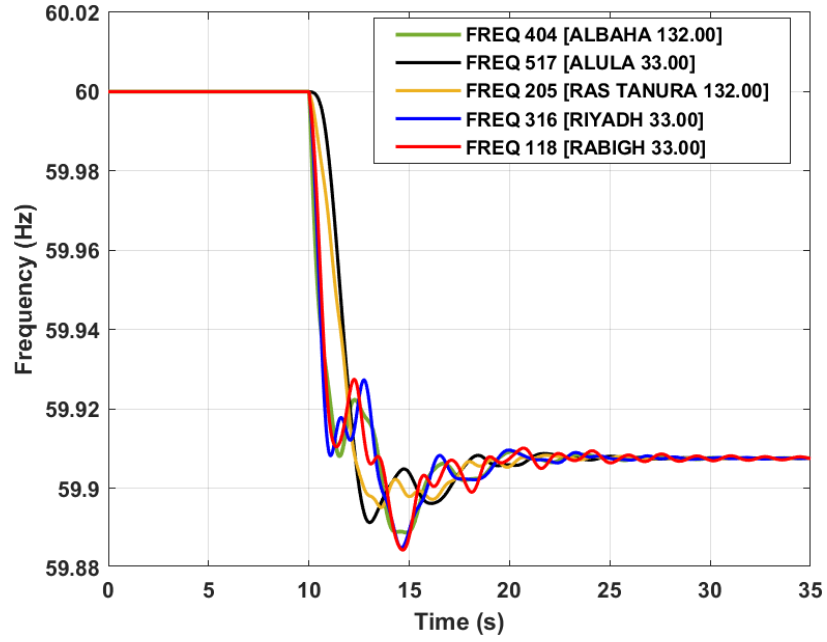


**Figure 3.12:** System voltage response after generator trip at bus 352 in the Central region.

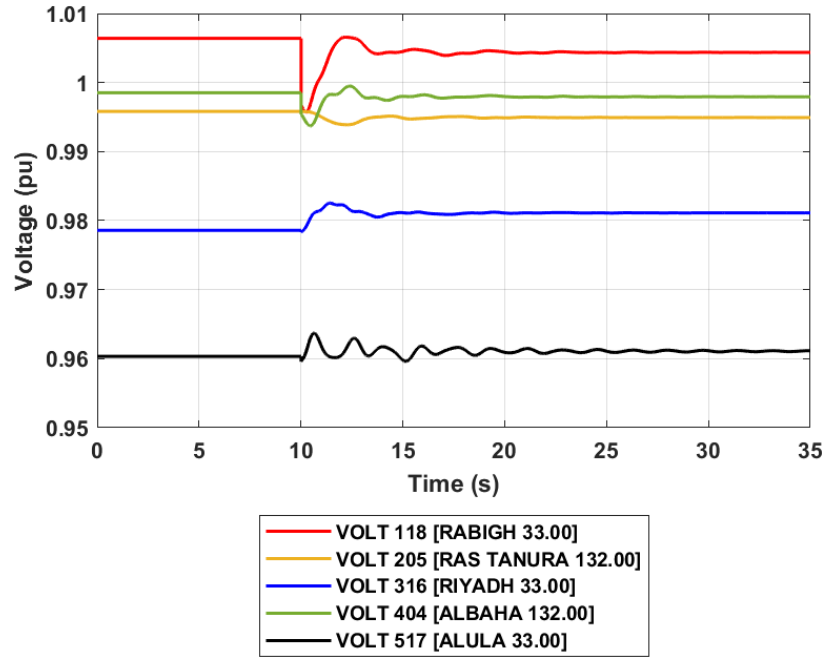
## 2) Second Case:

In the WOR region, specifically in the Jeddah city area, a generator at bus 117 (JEDDAH-3) experienced a trip. This generator has a capacity of 855.6 MW. Figure 3.13 illustrates the system frequency response 10 seconds after this event in the five operating regions, representing the frequency response in the WOR (JEDDAH bus), NOR (NEOM bus), EOR (JUBAIL bus), SOR (ABHA bus) and COR (RIYADH bus) regions. The system is suddenly unable to supply enough active power (real power) to meet the demand, leading to a frequency drop. The RABIGH bus (118), located relatively close to the tripped generator in the western region, showed a more pronounced frequency drop, stabilizing more slowly compared to buses in other regions due to its proximity to the disturbance. In contrast, the ALULA bus (517) in the Northern region, farther away from the tripped generator, experienced minimal frequency impact, showing a stable response during the event.

In the same scenario, Figure 3.14 reveals the voltage magnitude response. The RABIGH bus (118) experienced a slight drop in voltage, fluctuating within a range of around 1.0 per unit. The voltage levels in other regions, such as ALBAHA (404) and RIYADH (316), remained unaffected, underscoring the localized impact of the trip only in the Western region.



**Figure 3.13:** System frequency response after generator trip at bus 118 in the Western region.

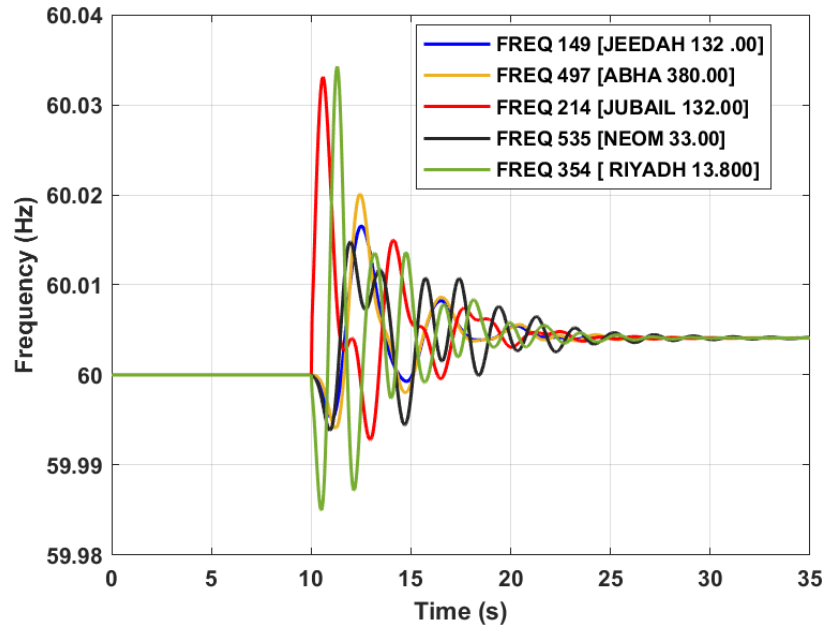


**Figure 3.14:** System voltage response after generator trip at bus 118 in the Western region.

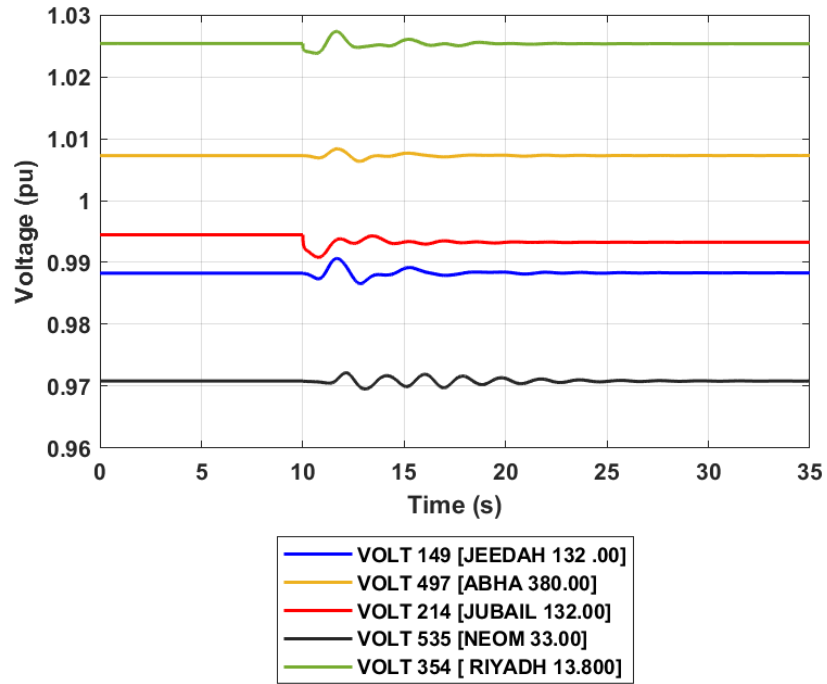
## Line Trip Event Scenarios

### 1) First Case :

The first case is to trip a transmission line between cities in different operating regions. After ten seconds, a transmission line is tripped between RIYADH bus 338 in the COR region and DAMMAM bus 293 in the eastern region. This transmission line carries 516 MW of power. Figures 3.15 and 3.16 present the simulation results for the frequency system and the magnitude responses of the voltage, respectively. This is because this transmission line transmits a large quantity of MW. The frequency of RIYADH bus 354 and JUBAIL bus 214 reached an oscillation between 59.985 and 60.033 Hz, while the other responses outside the region were only slightly affected because they are out of region and there is no direct connection with those buses. The figure shows that the voltage on the JUBAIL bus dropped from 0.995 to 0.993 pu, but the voltage responses of the other two buses are not greatly affected. In this case, during line trips, the frequency typically does not decrease. Line trips mainly affect power distribution and routing, but do not inherently disrupt the balance between overall generation and demand.



**Figure 3.15:** System frequency response after line Trip between bus 338 and bus 293 in different region

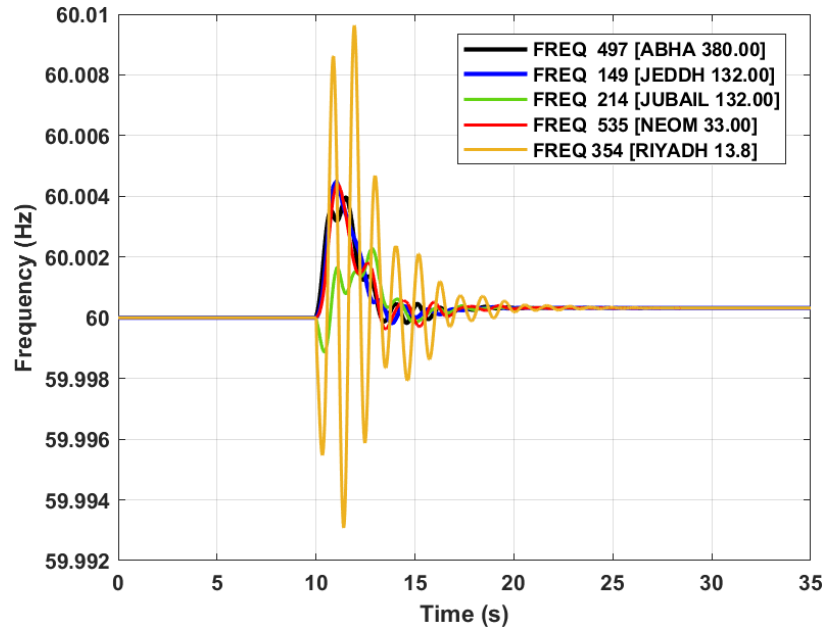


**Figure 3.16:** System voltage response after line Trip between bus 338 and bus 293 in different region

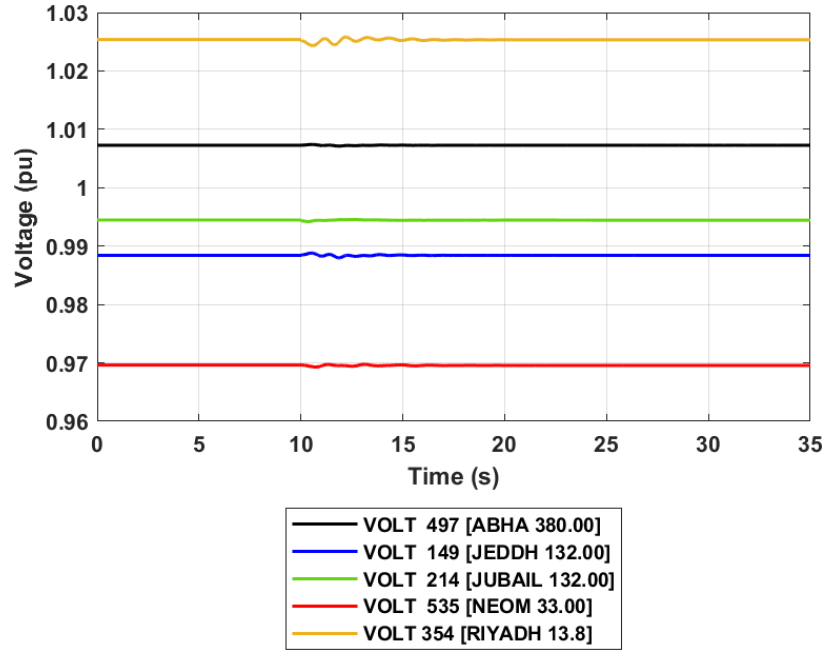
## 2) Second Case:

In this case, a transmission line between Bus 341 and Bus 350 within the RIYADH region. This line carries approximately 470 MW of power. Figures 3.17 and 3.18 present the simulation results, which illustrate the frequency and voltage magnitude responses, respectively. After the line trip, an immediate disturbance in frequency occurs. The frequency at RIYADH bus 354 shows oscillations between 59.992 and 60.008 Hz, indicating a local impact due to the high power transfer through the affected line. Other buses in different regions, including JUBAIL bus 214 and JEDDAH bus 149, also exhibit slight frequency oscillations as the system attempts to stabilize. Buses farther away, such as those in ABHA and NEOM, are less affected by the trip, showing only minimal variations. On the other hand, voltage response at various buses. The voltage at the RIYADH bus remains mostly stable, with only minor fluctuations around 1.02 pu, indicating that in the voltage stability refers to that voltage is not affected and still stable because of that other generators in the grid are still maintaining the voltage levels.





**Figure 3.17:** System frequency response after line trip between bus 341 and bus 350 in the same region

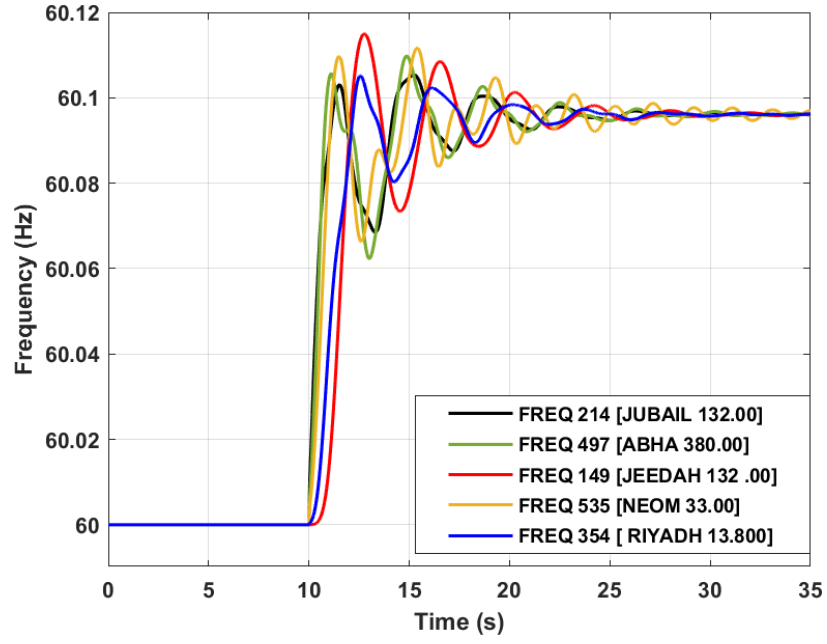


**Figure 3.18:** System voltage response after line trip between bus 341 and bus 350 in the same region

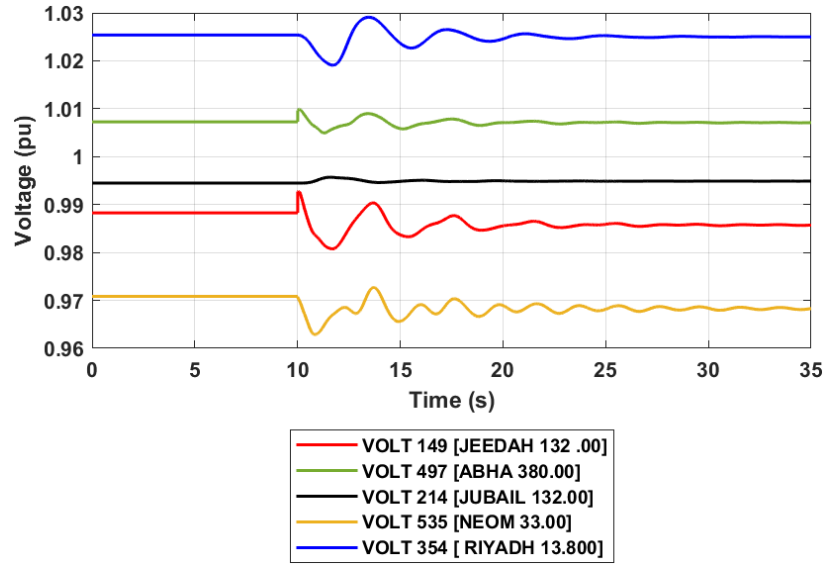
### 3.3.4.3 Load Shedding Event Scenarios

#### 1) First Case :

Load shedding events involve the disconnection of loads at certain buses. After a duration of ten seconds, the load of 772 MW located on MADINAH bus 106 inside the western operating region is reduced. Figure 3.19 illustrates the frequency responses of different buses. It can be seen that the frequency grew to 60.1146 Hz before it peaked and then dropped down after 30 seconds to 60.0958 Hz, especially for the JEDDAH bus, which is close to the event area. The voltage responses of the same buses after load disconnection are shown in Figure 3.20. The figure shows that the voltage on the JEDDAH bus fluctuated between 0.9808 and 0.9926 pu, but the voltage responses of the other buses are not greatly affected. The remaining generation capacity exceeds the reduced demand, causing a temporary increase in the frequency of the system. This frequency rise occurs because the balance shifts toward excess generation, leading to an increase in frequency until the system adjusts and stabilizes.



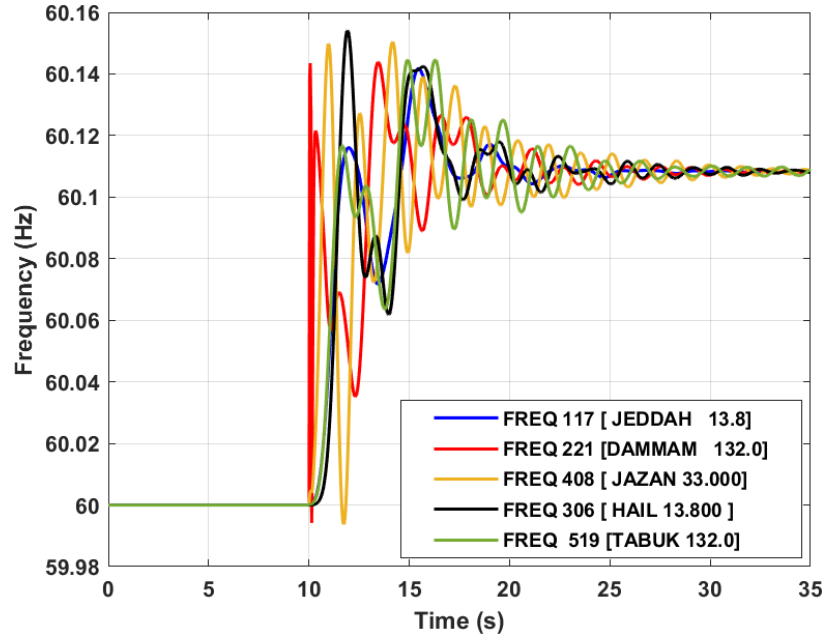
**Figure 3.19:** System frequency response after load disconnection at bus 106 in the Western region.



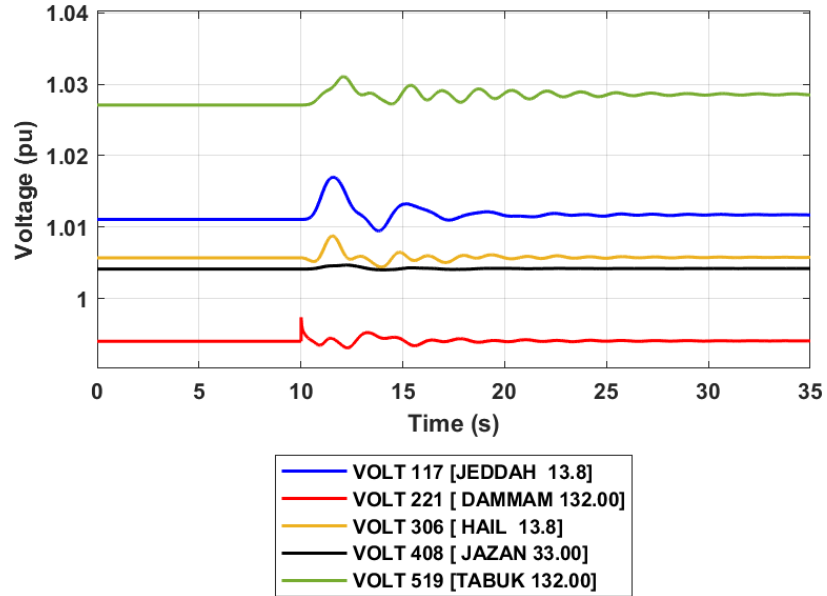
**Figure 3.20:** System voltage response after load disconnection at bus 106 in the Western region.

## 2) Second Case:

In this case, load shedding occurred at the JUBAIL-2 bus 230 in the EOR region, involving the disconnection of a load of 922 MW. The frequency and voltage responses of several buses in the JEDDAH, DAMMAM, HAIL, JAZAN, and TABUK areas are observed in Figure 3.21 and Figure 3.22, respectively. After the load-shedding event, the frequency of nearby buses temporarily increases due to the sudden reduction in demand. The system frequency rises above the nominal 60 Hz, with a peak frequency observed at the JEDDAH bus. This transient rise occurs due to excess generation following the load disconnection. Over time, the system frequency gradually stabilizes as the system balances itself, eventually returning close to the nominal value after around 30 seconds. In the voltage responses observed for the affected buses, the voltage at JEDDAH shows a fluctuation in response to the load shedding event, oscillating between a minimum and maximum value before stabilizing. However, voltage responses at other buses are less significantly affected and remain relatively stable with minimal fluctuations.



**Figure 3.21:** System frequency response after load disconnection at bus 230 in the Eastern region.



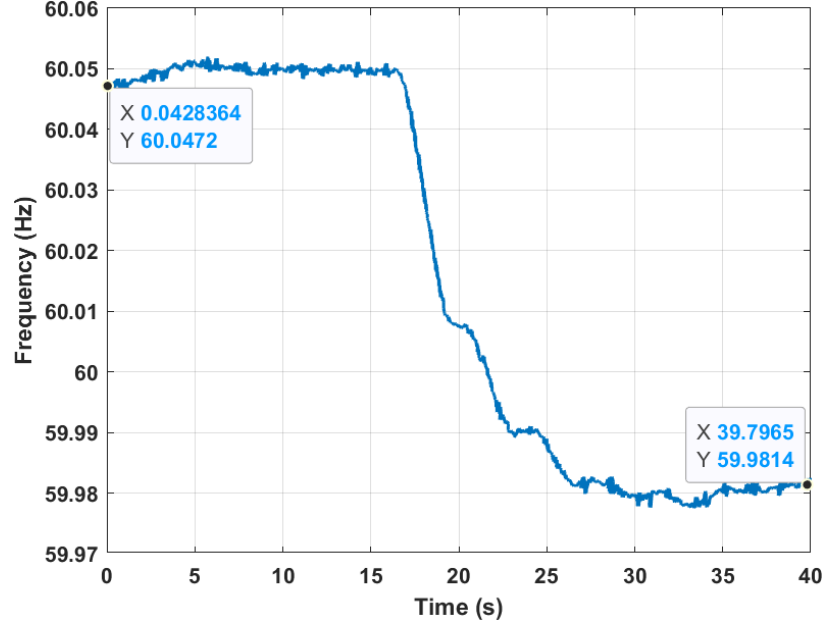
**Figure 3.22:** System voltage response after load disconnection at bus 230 in the Eastern region.

### 3.3.5 Model Validation Case of Saudi Synthetic Electric Grid

The standard approach to verifying a power flow scenario is to use it to replicate specific system situations at a particular moment in past situations (referred to as a snapshot) (57). Fault data reports were requested from one of the electricity associations in Saudi Arabia but were not obtained. Therefore, getting detailed frequency response fault reports from reliable sources is difficult because this information is usually private and sensitive. This limits access to accurate data for modeling validation, which often causes it not to match the actual observed event for several reasons like initial power flow conditions, mismatched sequence of actions, and or not similar accuracy of the mode. Consequently, if accurate data are provided regarding these events, this synthetic Saudi model would provide a more accurate picture as an actual system.

This synthetic dynamic model was validated with a real frequency incident that occurred as shown in Figure 3.23, in which the blue line indicates the 333.4 MW generation trip event that occurred in the Central region, Unit 1, at 14:20:48 UTC, 2016-08-09. The initial frequency was 60.0472 Hz, while after disturbance the frequency decreased to 59.980 Hz (58).

Since the amount of MW has dropped and the data of the average frequency deviation which is the pre-disturbance frequency and the post-disturbance frequency are available in this case, the characteristic of the frequency response of the system  $\beta$  can be calculated. The constant  $\beta$  describes the relationship between generation loss and frequency deviation during unit MW / Hz (59).



**Figure 3.23:** Nominal data for the 333.4 MW generation trip event that occurred at Unit 1 in the Central region at 14:20:48 UTC on 2016-08-09

$$\beta = \frac{\Delta P}{\Delta f} \quad (3.1)$$

Where:

- $\Delta P$ : Change in active power (MW)
- $\Delta f$ : Frequency deviation (Hz)

Thus:

$$\Delta P = 333.4 \text{ MW}$$

$$\Delta f = 0.0672 \text{ Hz} = 67.2 \text{ mHz}$$

$$\beta = 4961.3 \text{ MW/Hz}$$

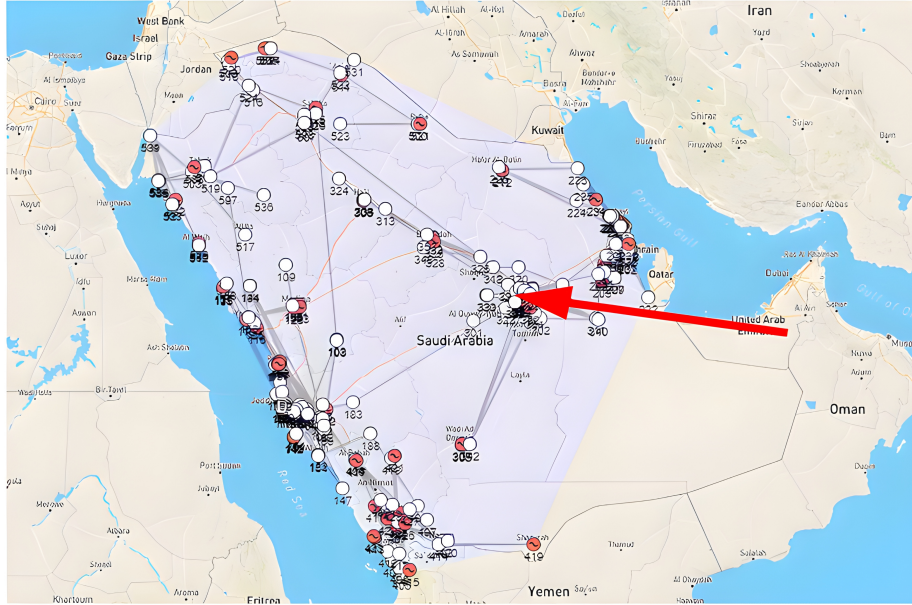
Thus, the characteristic of frequency response refers to  $\beta = 4961.3 \text{ MW / Hz}$ , as well as the average frequency deviation  $\Delta f$  is 67.2 mHz.

The frequency response is mainly affected by the inertia constant of the system, the dynamics of the turbine-governor, and the load compositions. The inertia constant of the system indicates the ability to resist frequency changes, whereas the turbine-governor settings influence the speed of the response to disturbance of the system (60). While, in (61) indicates that the turbine-governor and load compositions have a relatively small and bounded effect on the frequency deviation, the inertia constant significantly influences the system frequency response, especially during disturbances in an unstable power system.

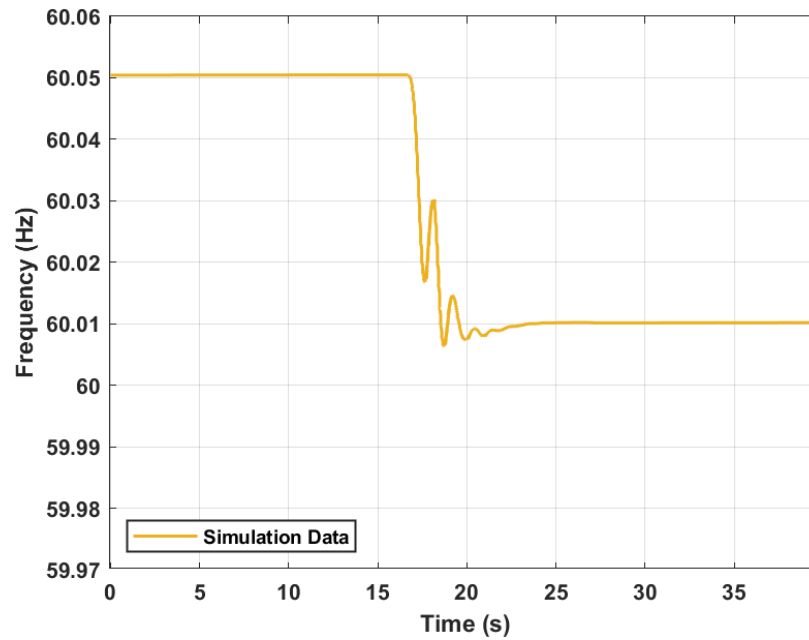
A generator disconnect incident was conducted in the central region in SSEG to simulate the real event where bus 315, which generated 333 MW, was tripped. Figure 3.24 demonstrates the location of the disturbance and Figure 3.25 shows the initial response of the SSEG system before modifying the parameters where the initial parameters represent the default parameters for a dynamic model.

The comparison between nominal and simulation data, which is in COR, is shown in Figure 3.26. This graph shows a frequency difference between the results of the nominal and simulation data results as well as demonstrates that the slope of the decline in frequency of the simulation response was not as steep as the measurement result.

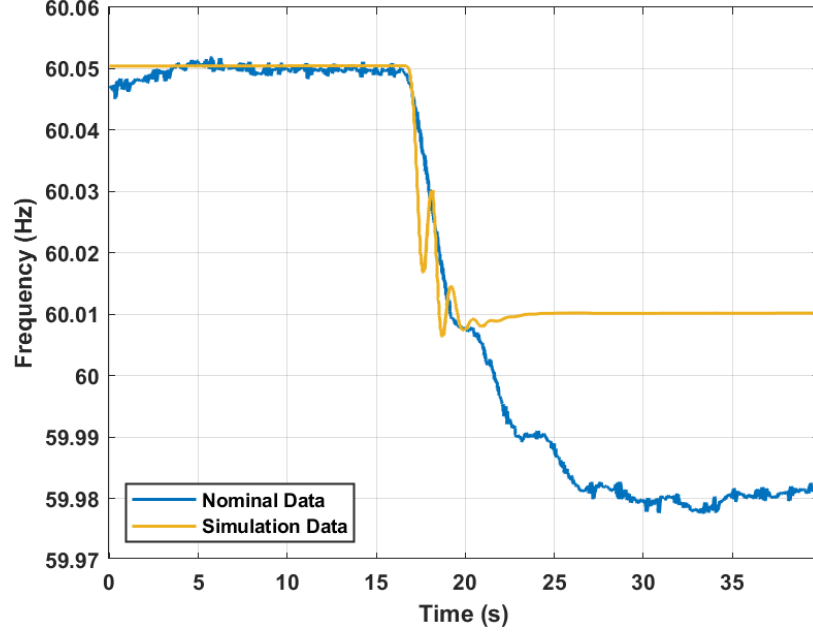




**Figure 3.24:** The location of the disturbance at bus 315 generation amount 333 MW



**Figure 3.25:** Shows the dynamic behavior of SSEG before modification.



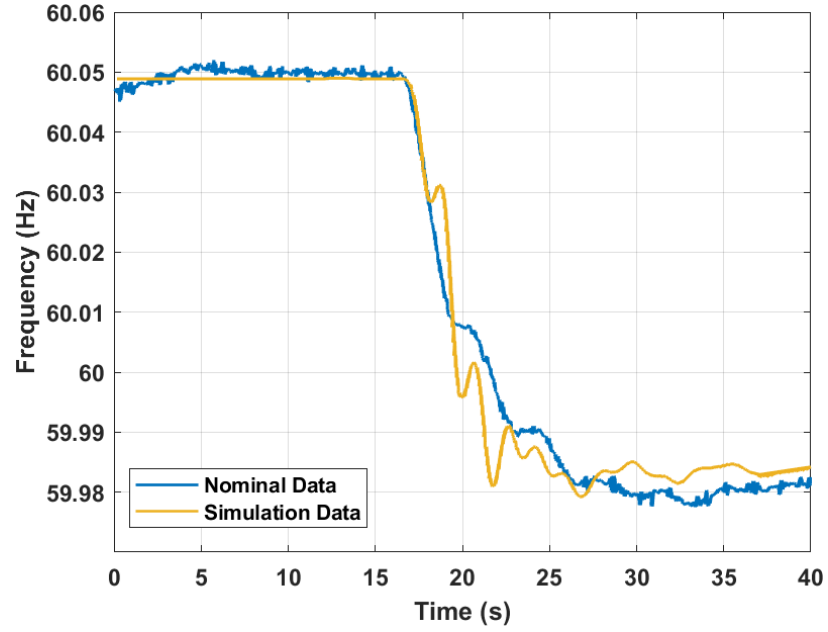
**Figure 3.26:** Shows simulation and nominal data comparison of cases before modification

As mentioned above, real dynamic parameters were not available, so typical dynamic parameter parameters were used. The parameters of the synthetic model have been modified to reflect the dynamic characteristics of the real Saudi power system. To reach a steeper enough like the nominal result, the system inertia constant was decreased for all generators to about 48% of the original value. Additionally, the number of turbine-governors was reduced, with the total generation capacity equipped with active turbine-governors to 22.28% of the total system capacity.

- Total generation capacity for the system ( $P_{\text{Gen}}$ )= 64,637 MW
- Total MW amount with active Turbine Governors = 14,402 MW

$$\left( \frac{14,401}{64,637} \right) \times 100 = 22.28\%$$

Figure 3.27 shows the simulation and the comparison of the nominal data of the cases. Thus, it can be observed that after modifying the parameter model, the simulation frequency response closely resembles the real response.



**Figure 3.27:** Shows the dynamic behavior of SSEG after modification

## 3.4 Summary

This chapter represents an initial step to constructing synthetic power system grids for the Saudi electric grid that are geographically and statistically reasonable. The model is designed accurately to similar the detailed characteristics according to the geographical constraints of real Saudi power systems, including compliance with Saudi code requirements and statistical properties simulated in actual power grids using the CURENT Large-scale Testbed (LTB) platform. The following are the points that have been implemented in this chapter :

- The dynamical synthetic grid model is built and subjected to different disturbances in different parts of the system to verify the stability of this synthetic model. The simulation results shown in this chapter confirm that the system is dynamically stable.
- The results of simulations presented in this research emphasize that validates the system under investigation illustrates dynamic stability based on code requirements.
- The 224-bus synthetic Saudi electric grid model represents geographic coordinates, load and generation profiles, and the results accurately represent the geographic constraints as similar real systems.
- In future research, there is potential to extend this model to create test cases for various domains within power systems research and for educational purposes.

## Chapter 4

# ASSESSMENT OF WIND TURBINE FARMS INTEGRATION, AND GRID CODE COMPLIANCE IN THE SAUDI SYNTHETIC ELECTRIC GRIDS

## 4.1 Overview

This chapter explores the critical aspects of integrating wind power farms into the Saudi Arabian grid, focusing on compliance with the requirements of the grid code. The study evaluates the unique challenges caused by the characteristics of wind turbine generators compared to conventional synchronous generators. The emphasis is on assessing the failure carry capability and the reactive power capability of wind farms to ensure the security and reliability of the power system. Through detailed simulations. This chapter employs a simulation approach to model and test the requirements of the wind grid code for planned wind power projects in the North Saudi Arabian region (NOR).

## 4.2 General Background

Saudi Arabia is strategically diversifying its energy by incorporating renewable sources, such as wind power. The commitment to the sustainability of the country has led to the development of wind power projects, prompting the need for a nuanced examination of their integration with the existing Grid Code. Wind Turbine Generators require a tailored set of provisions to ensure seamless integration into the Saudi Transmission System. therefore. The chapter provides an overview of the historical and advantages context of wind power in Saudi Arabia, The country underscores the motivations behind the push for renewable energy and the challenges in aligning wind turbines with the Saudi Power System.

## 4.3 Motivations

- Representing a simulation of one of the future wind farm projects in Saudi Arabia.
- Evaluate technical and operational obstacles associated with integrating wind power into the existing Saudi power grid infrastructure.
- Assess simulation results to emphasize the wind power operating system with the unique characteristics of the Saudi grid code.
- Investigate the ability of wind turbine farms to remain operational and maintain grid stability during transient faults or disturbances in the power system.
- Comparison of Low-Voltage Ride-Through Capability (LVRT) requirements across different grid codes to encounter differences in terminology, thresholds, testing procedures, and other technical specifications.

## 4.4 Historical and future of Wind power farms in Saudi Arabia

It is widely recognized that oil rich countries like Saudi Arabia depend on coal, oil, and gas, which contribute to 2 ° C emissions and global warming. The Paris Agreement, established in 2015, requires the reduction of carbon dioxide and the increase in global temperature below 2 ° C per year (62; 63).

It is referred to that Saudi Arabia plays a necessary role in this deal. It produces an estimated 278 million tons of CO<sub>2</sub> annually, so it ranks in the 11th grade of CO<sub>2</sub> emission (64). In addition, it is expected to increase its production to double by 2023. Furthermore, the Saudi 2030 vision calls for increased renewable energy instead of fossil fuels (4).

Although it is primarily known for its major oil reserves, Saudi Arabia recognized the potential of wind energy to contribute to its energy while also addressing environmental concerns and promoting sustainable development. In recent years, it has been gradually diversifying its energy portfolio, in order to reduce its dependence on fossil fuels and embrace renewable energy sources, including wind power (65). The vast land area of Saudi Arabia with a total area of around 2,000,000 square kilometers and its strategic geographical location make it conducive to the development of wind energy (5; 66). Thus, in 2021, Saudi Arabian unveiled plans to invest in renewable energy projects, including wind farms, as part of its Vision 2030 initiative (67). This initiative aims to transform the Saudi economy and reduce its dependence on oil revenues.

In recent years, the Saudi wind energy sector has experienced growth, thanks to favorable government policies and strategic partnerships with international stakeholders. Programs like the National Renewable Energy Program (NREP) were critical in encouraging the development of wind energy projects throughout the nation (6; 68). In addition, the evolution of wind turbine technology and the decrease in costs have made wind energy a more attractive option for investors and energy markets. Collaborations with investors and energy markets, including Aramco and the General Authority of Statistics, have been vital in the promotion of wind energy in Saudi Arabia. These associations have contributed to the advancement



of wind energy projects and easing the shift toward renewable energy sources. Moreover, investments in research and development by institutions such as King Abdullah City for Renewable Energy (K.A.CARE) and the King Abdullah Petroleum Studies and Research Center (KAPSARC) have led to technological innovations in the sector of wind energy, further enhancing the capabilities of Saudi Arabia in renewable energy (43; 15).

## 4.5 Advantages of wind energy in the Saudi electricity grid

### 4.5.1 Wind Energy Map and Wind Speed Data in Saudi Arabia

Understanding the locations and geography is critical to determining the future of alternative energy in any country. Saudi Arabia, with its unique weather and geographical characteristics, is a windy country that experiences high atmospheric pressure (27). The data provided can help assess the potential significance of wind energy in creating the future economics of the kingdom. The country lies between latitudes 17.5 ° N and 31 ° N and longitudes 36.6 ° E and 50 ° E. Its terrain varies, with a height ranging from sea level to 2,600 m (28). According to these data, Saudi Arabia is unique due to its strategic location and the potential to use a variety of renewable energy sources. Many areas in the kingdom have significant capacity for wind energy generation.

These studies (66; 69). conducted the wind speed in Saudi Arabia in 2020, measuring the average wind speed in most areas. This is a study that used hourly averaged wind data

collected from 46 weather stations throughout Saudi Arabia from 1980 to 2019 to create a detailed wind map of the country. The Inverse Distance Weighted Interpolation Method (IDW) was used to estimate wind speeds between the stations, allowing for the conversion of point data into a raster format. The resulting wind data were categorized into nine classes, where the wind speed was measured at altitude 50 meters above ground level, ranging from 3.7 to 6.4 m/s. The highest classes, indicating wind speeds between 5.8 and 6.4 m / s, were identified as excellent for wind farm locations, especially in eastern and central Saudi Arabia, with some areas along the northern border and the region of the southern north coast also showing potential. In contrast, the southern coastal area was considered to have poor wind resources (70).

The recent study (70; 27). is focused on evaluating wind resources and economic benefits in 10 locations across Saudi Arabia. It uses wind speed data measured at 40, 60, 80, and 100 meters above ground, along with temperature, pressure, and relative humidity near the ground, to assess the technical and economic feasibility of implementing wind power at these sites.

Table 1 in the appendix, collected from multiple references (71; 72; 73), presents wind speed data at 100 m and 150 m above different ground levels in 34 cities. The annual average wind speed at or above 100 m is above 6.0 m/s at all locations, except for those in the southern sector and the central region. The top five locations in terms of average annual wind speed at 150 m are Neom (8.38 m/s), Afif (9.22 m/s), Tarif (8.28 m/s), Al Ghat (9.04 m / s) and Wadi Ad Dawasir City (8.87 m/s). Wind speeds above 6.0 m/s were observed in Tarif, Al Jawf, Hafar Al Batin, and north Yanbu. This ensures that the wind farms at these

locations, which will be built using 3.5 m / s cutting-speed wind turbines, can produce power during the year. Therefore, the study recommends potential locations for the deployment of wind farms in Saudi Arabia in preference order such as North Yanbu, Al Ghat, Wadi Ad Dawasir, Tarif, Neom City and Ad Dawadmi.

#### **4.5.2 Potential Locations of future Wind Energy Projects**

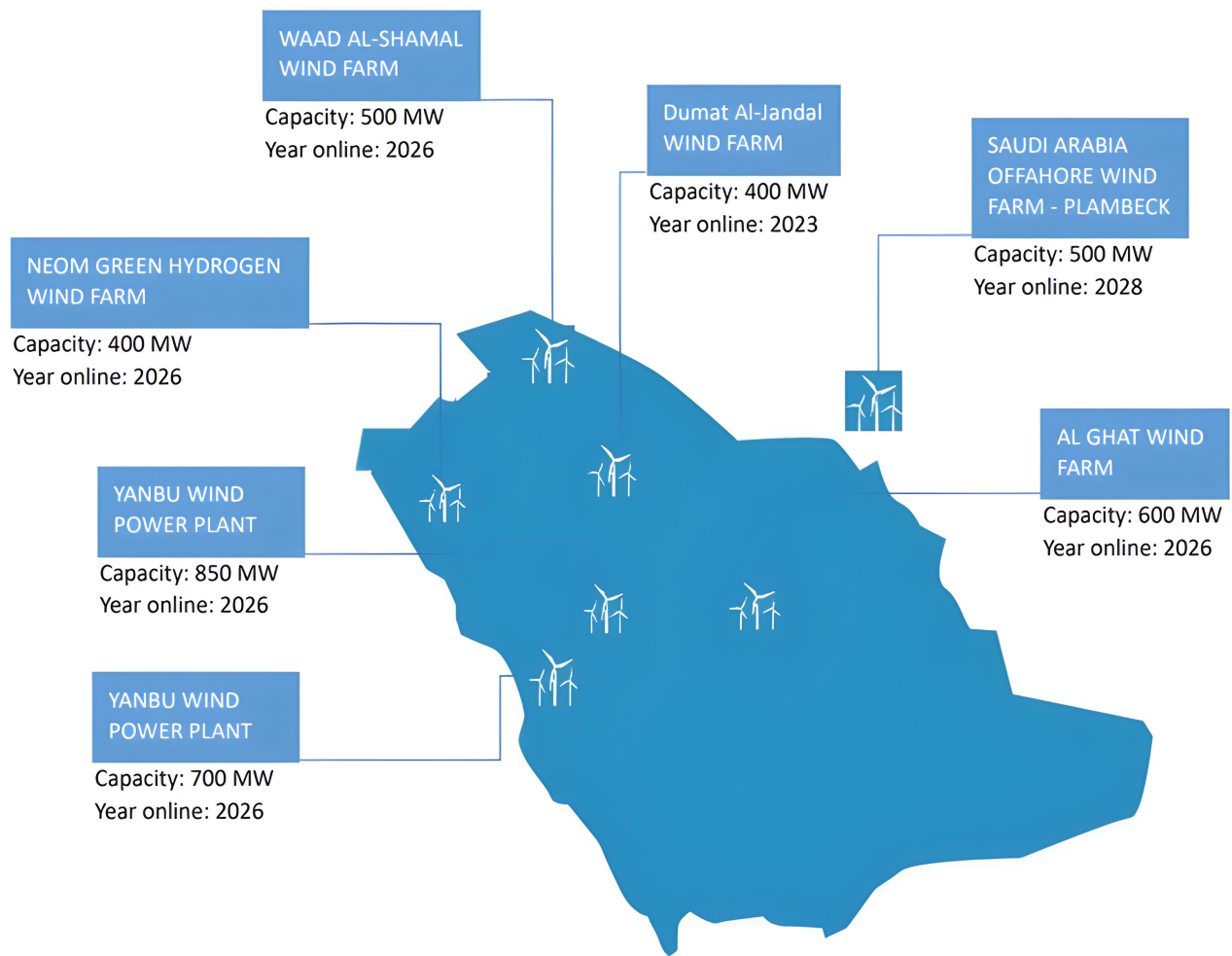
Choosing the optimal location and height of the turbine for wind power plants requires a multiple analysis that integrates environmental, technical, and economic factors (74). As mentioned in (27), sites are typically selected based on their exposure to reliable wind resources, which are often determined by collecting long-term wind speed data at various heights. In addition, economic considerations are equally important in selecting sites. More importantly, technical and engineering factors also play a critical role in the decision-making process. The height of wind turbines is selected based on the wind profile of a location, which can vary significantly with altitude (70; 27; 75). The tallest turbines can capture more consistent winds at greater heights, potentially generating more power. This section presents the results of the wind farm site selection conducted in Saudi Arabia over the past five years, which has been studied from many aspects.

According to (70), a comprehensive evaluation and analysis was conducted in 2020 to assess the monthly wind speed and power density at a height of 100 m in various locations in Saudi Arabia. Based on estimated wind speed and power levels, the study analyzed the feasibility of installing large, medium, and small-scale wind turbines at 12 different sites. Recommendations were provided for a selection of regions.

As (76) shows, the Saudi Arabia power plant map for 2023 is a detailed high resolution of numerous planned wind, solar, oil and gas power plant projects that are expected to be operational by 2028. As part of its Vision 2030 initiative, Saudi Arabia is focused on developing 14 GW of solar power, 9 GW of gas based power, and 5 GW of wind power. This map was first published in The Energy Year of Saudi Arabia 2023.

The study of speed wind is presented in (69) during six sites; Sharurah, Jeddah South, Al Wajh, Riyadh, Hafar Al Batin, and Al Jouf of Saudi Arabia is updated. Wind energy and its status were interpreted. The annual mean values of long-term wind speeds have varied between the years 2000 and 2020. Long-term wind speed values were found between 3.3 m/s in 2000 and 5 m/s in 2020. As a result, it was obvious that the promotion of a culture of wind energy for future development and installation is important to develop to minimize greenhouse gas emissions and support the national economy, which has an obvious impact on sustainability.

In 2024, Saudi Arabian continues to advance in its journey in wind energy, actively expanding its wind power capabilities and developing new projects. The road map for these future wind energy projects has been detailed in many sites in Saudi Arabia (77). As illustrated in Figure 4.1, future possible locations for wind energy projects in Saudi Arabia are highlighted, with current efforts and planned initiatives in various regions. These include expansions in cities like Neom City, Khafji, AlGhat, North Yanbu, and Tarif. The kingdom aims to further vary its energy (5; 78; 28). Despite challenges such as oil industry control and the need for more government incentives, Saudi Arabia shows its commitment to wind energy and highlights its determination to reach sustainable solutions.



**Figure 4.1:** Potential future locations for wind energy projects across Saudi Arabia.

## **4.6 Simulation and Assessment of the Saudi Arabian Grid Code Compliance of Wind Power Farms Connection in Transmission System**

### **4.6.1 Wind Power Farms Assessment into the Saudi Transmission System**

The penetration of wind energy into power systems in Saudi Arabia is increasing (79). This process in Saudi Arabia is particularly challenging due to the limited extension of the power system. Given the increasing interest in connecting wind farms to the Saudi Arabian electricity grid (SAGC), it has begun to modify or extend its own grid code to accommodate the particular capabilities and requirements of wind turbine generators (WTG) (29). This helps wind farm developers to benefit from a guide on the technical performance required of their plant when connected to and operating in the Saudi Arabian electricity system and participating in the electricity supply market.

Since the requirements for renewable power are set in the grid codes, the operators of power plants should take the responsibility to guarantee the compliance of the grid codes, and the operators of the system, in addition, should evaluate the effect of specific power plants on the operation of the power system in different situations (80). According to the Saudi Arabian Grid Code (SAGC), non-compliance of power plants with the grid code may lead to generation power being reduced even or disconnected from the grid. All generators

connected to the Saudi transmission system are required to comply with the grid code (29). With the expected high penetration of wind power, the simultaneous loss of wind farms generation will put at risk the security and reliability of the power system (81). Therefore, the main requirements for wind farm power plants concern the fault-ride capability, frequency operating range, and reactive power capability of wind turbines (82; 11). In order to measure scale of grid code compliance, objective and systematic standards about compliance testing and assessment are necessary. The objective of wind power farm connectivity testing is to evaluate the grid code compliance of wind energy grid integration technologies and to evaluate the potential challenges caused by the integration of wind power generation into power systems. The process of evaluating the electrical behavior of wind power plants that meet specific technical requirements in grid codes is also required to be specified (83). Generally, compliance tests for the renewable energy grid include mainly the power quality test, the active and reactive power test, and the low voltage test. (74).

#### **4.6.2 Representing the Synthetic Design Model for the NEOM Wind Farm**

In this section, aspects of the simulation model and approaches for modeling one of the future wind power projects in the Saudi Arabian power system and assessing grid code compliance are presented. Creating a simulation of a synthetic wind power plant is a complex but achievable task that combines physics simulation and software engineering (84). Such simulations can be valuable for educational purposes, design, and planning of real wind

power plants, or for public engagement and visualization. A specific case study is analyzed to identify the main requirements for the connection of the wind farm to the Saudi Arabian transmission grid.

A synthetic simulation of the NEOM wind power model was created, similar to that planned for the NEOM wind power project (85). As part of a larger global initiative to build the largest green hydrogen plant in the world, the NEOM wind power project incorporates wind energy as a key component. The project includes future expansion to accommodate, critical for powering the production of green hydrogen intended for global export as green ammonia by 2026 (86). The project is located in the north of the Kingdom of Saudi Arabia, with a capacity of 400 MW.

Due to the lack of complete and accurate data on the future NEOM project, a similar project was recently completed in 2023, which is the Dumat Al-Jandal wind power project, and is located 288 miles from the planned NEOM project. The data contained in the Dumat Al-Jandal project is used, Because the project is close to the project planned for the future, it has the same logistical, region, and climatic data (75; 16).

NEOM Green Hydrogen project in Saudi Arabia, as part of its initial phase, is planned to be powered by 4 GW of renewable energy from wind and solar sources. However, specific details on the number of wind turbines involved are typically not available in general descriptions of the project. The general capacity in terms of gigawatts is often highlighted, rather than the exact number of turbines (86).



## First scenario: Modeling of a Stand-Alone Wind Farm 400 MW a Synthetic NEOM Wind Power Dynamic Model

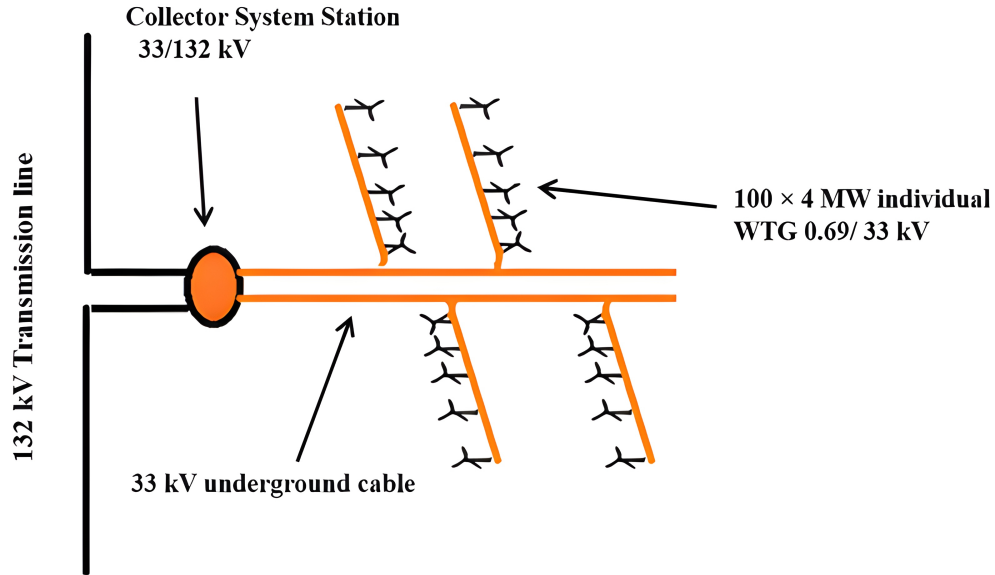
The study was implemented on the PSS®E platform. The model consists of two simulation data files: power flow data, dynamic data. With the aim of investigating the compliance of wind farms connecting to the Saudi Arabian transmission grid with the SAGC , the study considered the application for the 400 MW wind farm project for the so-called NEOM area, which is known to have a very high potential for wind energy (70; 27). The type 3 Generic Wind Turbine (Type-3 WTG ) wind turbine dynamic model is used, the block diagram of the model is detailed in (87). Table 4.1 shows the combination functions of the aggregated turbine model.

**Table 4.1:** Generic Wind Turbine (Type-3 WTG ) aggregated model combination functions.

| RES               | Model Combination | Function                  |
|-------------------|-------------------|---------------------------|
| <b>Type 3 WTG</b> | WT3G              | Generator/Converter Model |
|                   | WT3T              | Mechanical control        |
|                   | WT3P              | Pitch Control Model       |
|                   | WT3E              | Electrical control model  |

The connection configuration of the wind farms to the transmission grid is based on the requirements of the grid planning code and the wind code (88). A deterministic approach based on power flow studies is chosen. The selected connection configuration for the study case is based on main planning criteria: the N-1 Security criterion (the system should be able to withstand the loss of any single component such as a line, transformer, cable, or

generator). The N-1 security criterion is essential for the proper design of the transmission network to ensure the security and reliability of the power supply (89). System performance is compared to operating limits and criteria. Therefore, short-circuit calculations also play a very significant role in the proper selection of high-voltage equipment and the setting of protection relays (90). In Figure 4.2 the configuration of the wind farm connection to the 132 kV transmission grid is shown for the study case. The 33 kV wind farm collector bus is connected via two 100 MVA power transformers to the 132 kV transmission bus bar. The power generated by the wind farm will be transferred through two 132kV lines to two Bus 539 ( TABUK-SUBSTATION) and BUS 541 (DUBA-SUBSTATION) areas. The wind farm is planned to have 100 wind turbines, each rated at 4 MW. The general specifications of the NEOM wind farm are summarized in Table 4.2.



**Figure 4.2:** Diagram of Connection 400 MW a Synthetic NEOM Wind Power Farm with Transmission Grid.

**Table 4.2:** General Data About Synthetic NEOM Wind Power Farm

| Parameter                                                   | Value             |
|-------------------------------------------------------------|-------------------|
| Total wind power plant capacity                             | 400 MW            |
| Total number of wind turbines                               | 100               |
| Size of wind turbines                                       | 4 MW              |
| Number of substation transformers                           | 2                 |
| Size of substation transformers                             | 100 MVA           |
| Size of wind turbine transformers                           | 4.3 MVA           |
| Length of cables between wind turbines in the internal grid | 0.450 km – 1.8 km |
| Distance from substations POC                               | 47.8 km           |
| Voltage level at POC                                        | 132 kV            |
| Nominal operating frequency                                 | 60 Hz             |

### Modeling of Steady State and Dynamic Analysis

As shown in Figure 4.3. Each individual wind turbine generator (WTG) is connected to a 690 V bus and the WTGs are connected to the internal grid of the wind farm through their 0.69/33 kV step-up transformers. The internal grid is organized in eighteen rows or sections divided with four to eight WTGs in each section. Within the rows, the wind turbines are connected through 33 kV underground cables of different lengths and capacities depending on the location of each unit and the distance to the 33 kV collector bus. The power generated by the wind farm is sent through two 132kV lines to two buses Bus 539 (TABUK-SUBSTATION) and BUS 541 (DUBA-SUBSTATION).

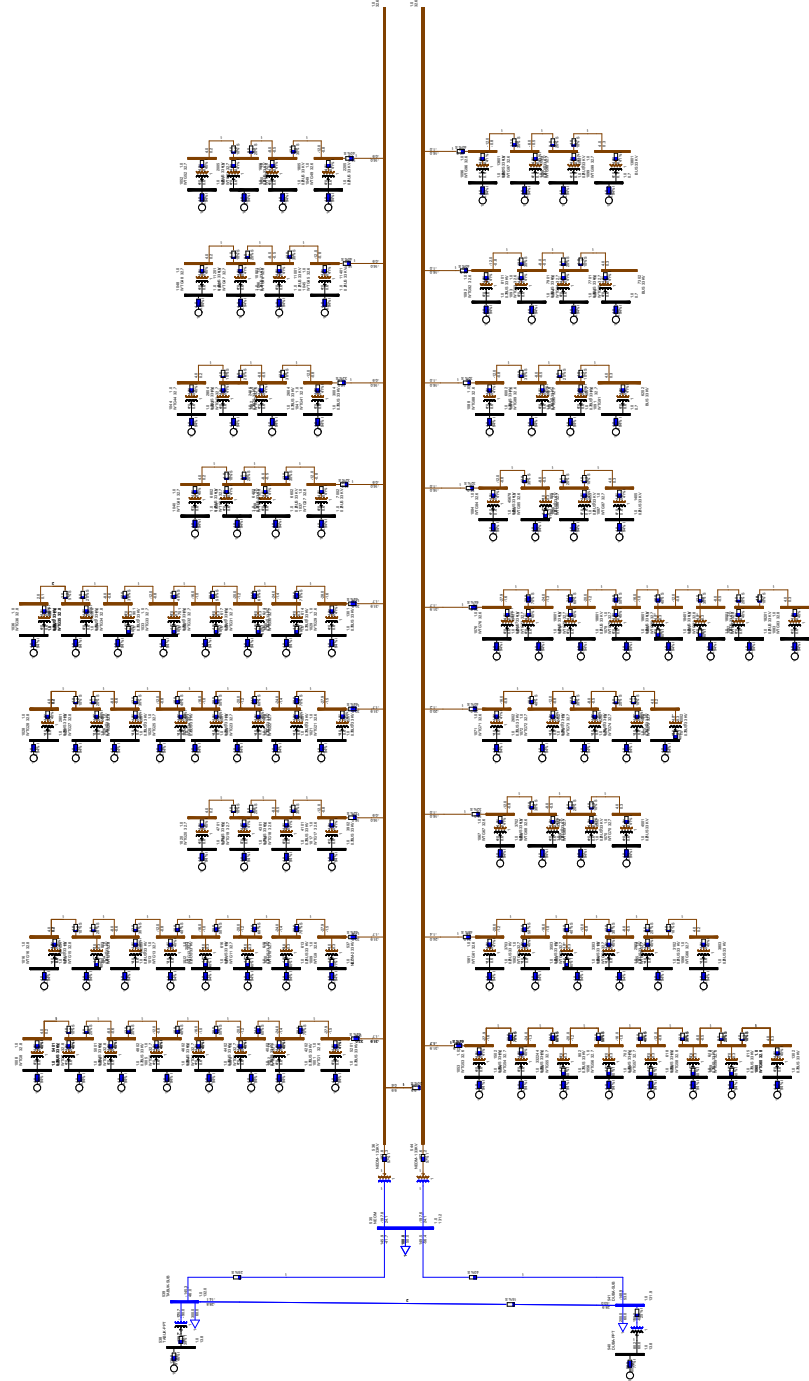
According to the power flow calculations, the reactive power absorption of some WTGs differs depending on the WTG terminal voltage level, as well as the length and capacitance of the 33 kV connection cables. The internal grid of the wind farm (without power transformers) absorbs 11.6 MVar of reactive power, with total active power losses of 3.8 MW at the

maximum output of wind farm power. The transformer and transmission line are not overloaded during normal system operating conditions. As a result, the voltage profile complies with Grid Code requirements.

The N-1 emergency procedure is applied to check system security, with the result that no transformer or line in the transmission network is overloaded for any emergency (89). The connection of the wind farm to two 132 kV lines ensures the N-1 safety standard in the event that one of the lines tripped due to an unplanned or planned outage.

In this study, some simulations are conducted to investigate the response of the WTG model to grid disturbances. The disturbance of most interest to the study is a symmetrical three-phase short circuit fault on the 132 kV bus. It is assumed that due to the protection reaction, the relay responds by disconnecting the wind turbine for 120 ms.

The main concern of operating with a high level of penetration of wind generation in the Saudi power system is related to the impact of wind power variability on the balance of the power system, given the current shortage of system regulation reserves. The variability impact issue on power systems is not addressed in this paper and will be covered in future work.



**Figure 4.3:** Aggregated model of 400 MW A synthetic NEOM Stand Alone Wind power Farm connected in transmission grid.

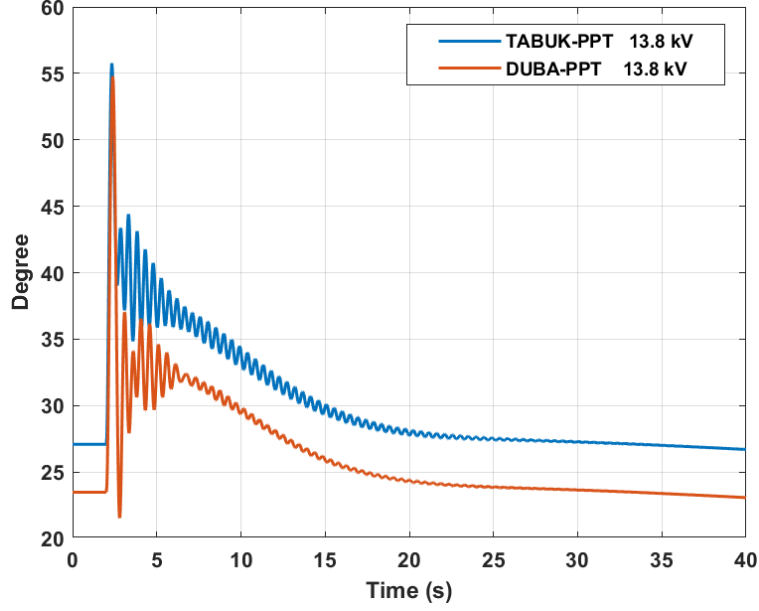
## Simulation and Results

Transient stability refers to the capacity of the power system to maintain synchronization when faced with significant transient disturbances. Stability depends on the initial operation and the magnitude of the disturbances (91). From the point of view of steady-state operation, wind power is similar to any other type of power generation. However, the response of wind turbines during and after disturbances differs from that of conventional generators (44). Transient stability studies often analyze ground-to-ground short circuits, both three-phase and single-phase. These faults are typically assumed to occur on the transmission line. Here, the fault is applied by disconnecting the affected line to isolate it.

For contingency simulations, the following were applied:

- The fault is a applied symmetrical three-phase that occurred on the shortest 132 kV line connected to the wind power plant.
- The fault is applied one second after the start of the simulation.
- The fault is cleared after 120 ms by tripping the faulted line.

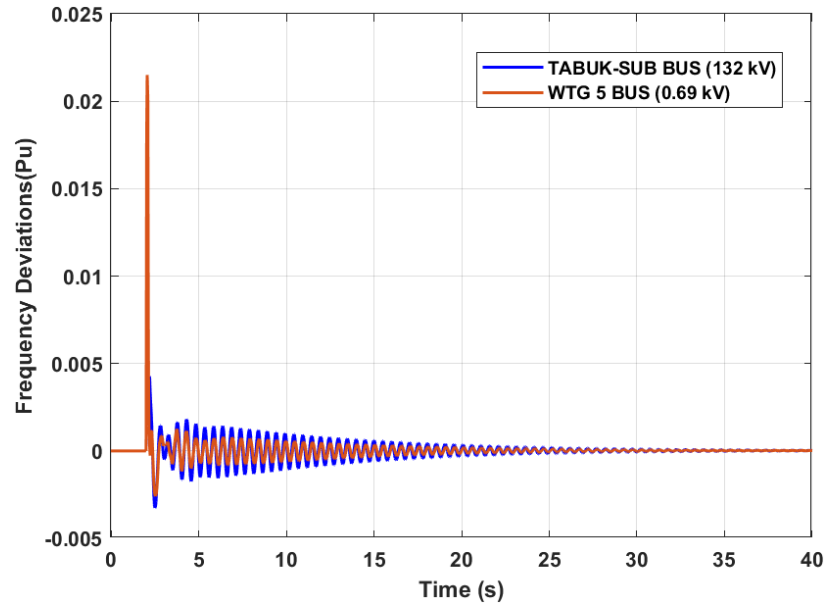
Figure 4.4 shows the angular response of the conventional generator rotor ( TABUK-PPT) and (DUBA-PPT) during the fault at 132 kV, as well as the initial increase being due to the imbalance caused by the fault. There is no significant impact on conventional generators that remain in synchronization. Therefore, there is no substantial effect on conventional generators that remain synchronized.



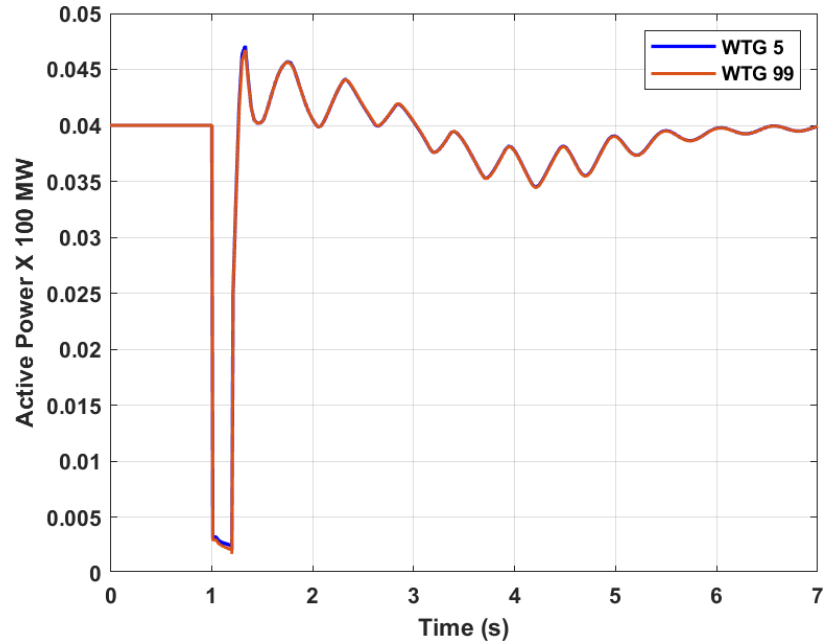
**Figure 4.4:** Rotor angular transient response of conventional generators during the fault of the stand alone wind farm

Figure 4.5 shows the transient frequency response after the fault occurs. At the time of the fault (around 0 seconds), both frequency deviations exhibit a sharp increase, especially noticeable on the WTG 5 bus at 0.69 kV (red line). This initial spike occurs because the fault disrupts the balance between generation and load, causing a sudden fluctuation in frequency. After about 10–15 seconds, the oscillations have dampened significantly.

Figure 4.6 illustrates the active power output of two wind turbine generators (WTG 5 and WTG 99) during a fault condition that suddenly decreases to a very low value of 0.004 pu. Due to the line trip, the voltage at the point of connection (POC) drops significantly. This voltage drop reduces the power transfer capability from wind turbines to the grid, causing the active power output to drop sharply. After the fault is cleared, the power output of both WTGs begins to recover and stabilizes over time. However, oscillations are observed before the system reaches a new steady state.



**Figure 4.5:** Frequency transient response after fault occurs in the 132 kV connection line of the stand alone wind farm

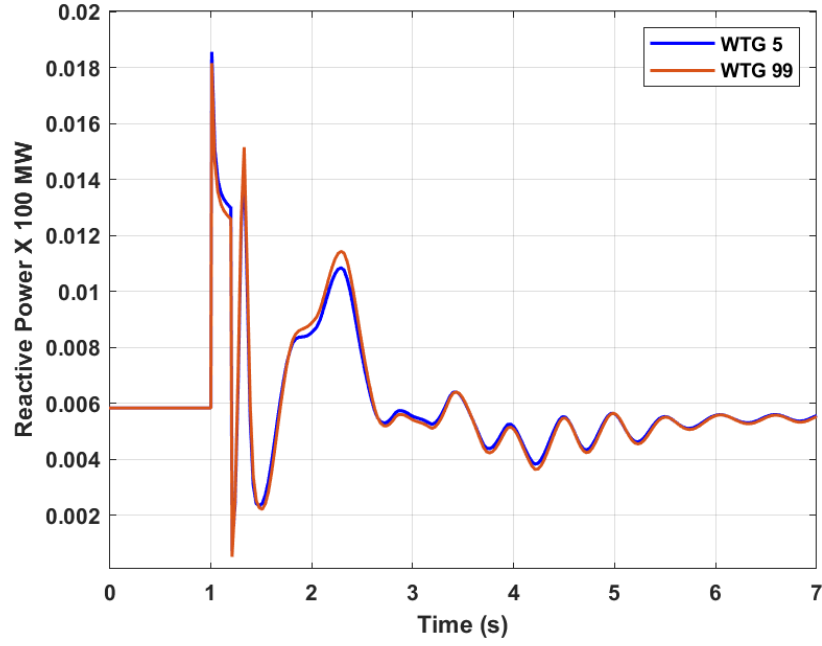


**Figure 4.6:** WTG active power response for two selected units WTG 5 and WTG 99 of the stand alone wind farm.

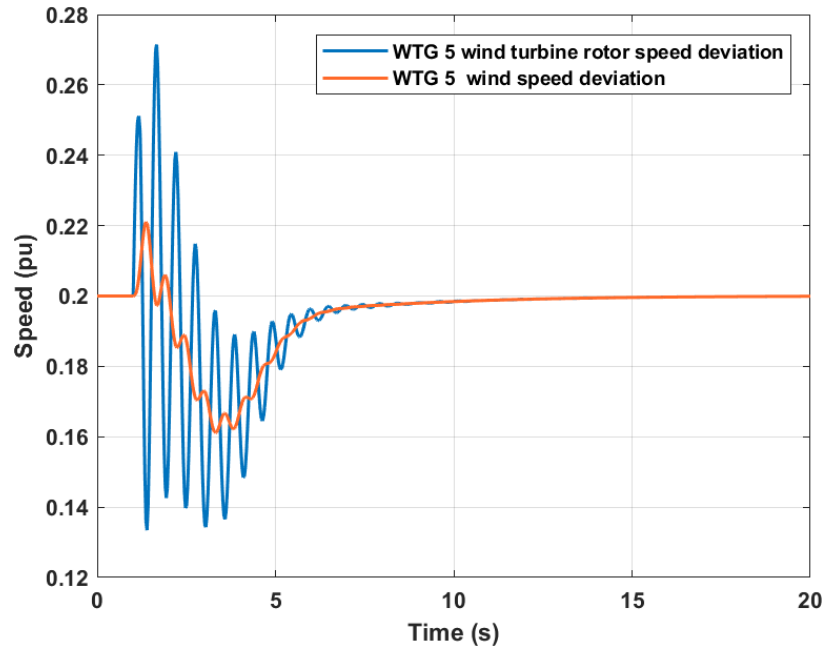


Figure 4.7 shows that before the fault occurs, the reactive power generated is close to zero. This is because the electric power has decreased to almost zero, whereas the mechanical power is assumed to be the same. As a result, the WTG unit during fault provides reactive power support to the grid 0.018 pu, as required by the wind grid code (92; 93).

Figure 4.8 shows the behavior of wind turbines in response to a disturbance. The generator speed is generally different from the rotor speed of the turbine. This difference is primarily due to the gearbox. Wind turbine speed refers to the rotational speed of the rotor blades of the wind turbine, driven directly by the wind. It is usually measured in revolutions per minute RPM. In contrast, generator speed refers to the rotational speed of the generator shaft, which is connected to the turbine by a gearbox or directly in direct-drive systems. It is also measured in RPM (94). The rotor speed deviation (blue line) shows oscillations that gradually dampen over time, whereas the wind speed deviation (red line) remains relatively stable after the initial disturbance. The difference between the mechanical input power and the electrical output power causes an increase in the rotor speed, and therefore the rotor starts to accelerate. In the 'Wind Turbine Farm' scenario, there is a sharp increase in the WTG 5 rotor speed deviation immediately after a disturbance, rising above 0.26 p.u. After this peak, there are significant oscillations in the rotor speed, which gradually decrease over time as the system attempts to stabilize. The oscillations in rotor speed gradually reduce in amplitude, showing a damped response over approximately 10 seconds. This damping effect indicates that the wind turbine control system is working to bring the rotor speed back to align with the wind speed (95; 96).



**Figure 4.7:** WTGs reactive power response for two selected units WTG 5 and WTG 99 of the stand alone wind farm.



**Figure 4.8:** Wind turbine speed and generator speed response of the stand alone wind farm.

## Second Scenario: Modeling of a 400 MW wind farm and 250 MW solar PV with a synthetic oxygen NEOM dynamic model

### Modeling of Steady State and Dynamic Analysis

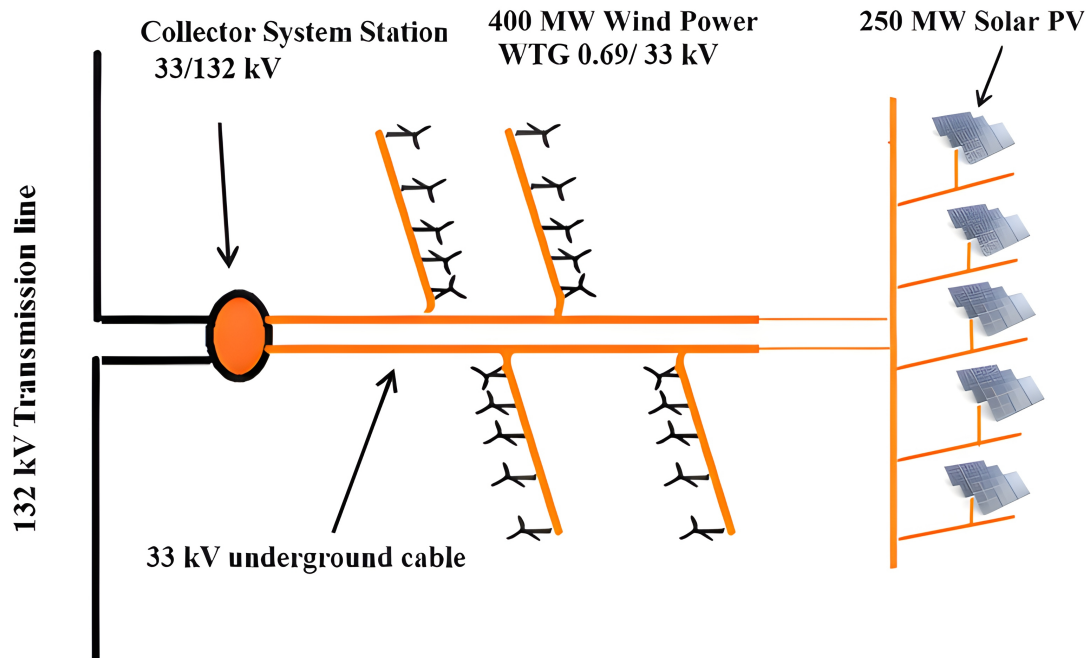
According to Oxagon, future projects in NEOM. It operates entirely on around 4 GW of renewable electricity generated by combining both on-site wind and solar plants (78). A synthetic model was assumed to be built to simulate this project. Additionally, to investigate the compliance of wind farms and solar power plants connected to the Saudi Arabian transmission grid with SAGC, the study considered the application of a 650 MW project by adding 250 MW of solar power to the previous model in the first scenario to simulate the Oxagon project (70; 27). A Generic Wind Turbine (Type-3 WTG) and generic models (PV plants) were used (87). As Table 4.3 shows, (PV Plants) model combination functions.

**Table 4.3:** Generic Models (PV Plants) aggregated model combination functions.

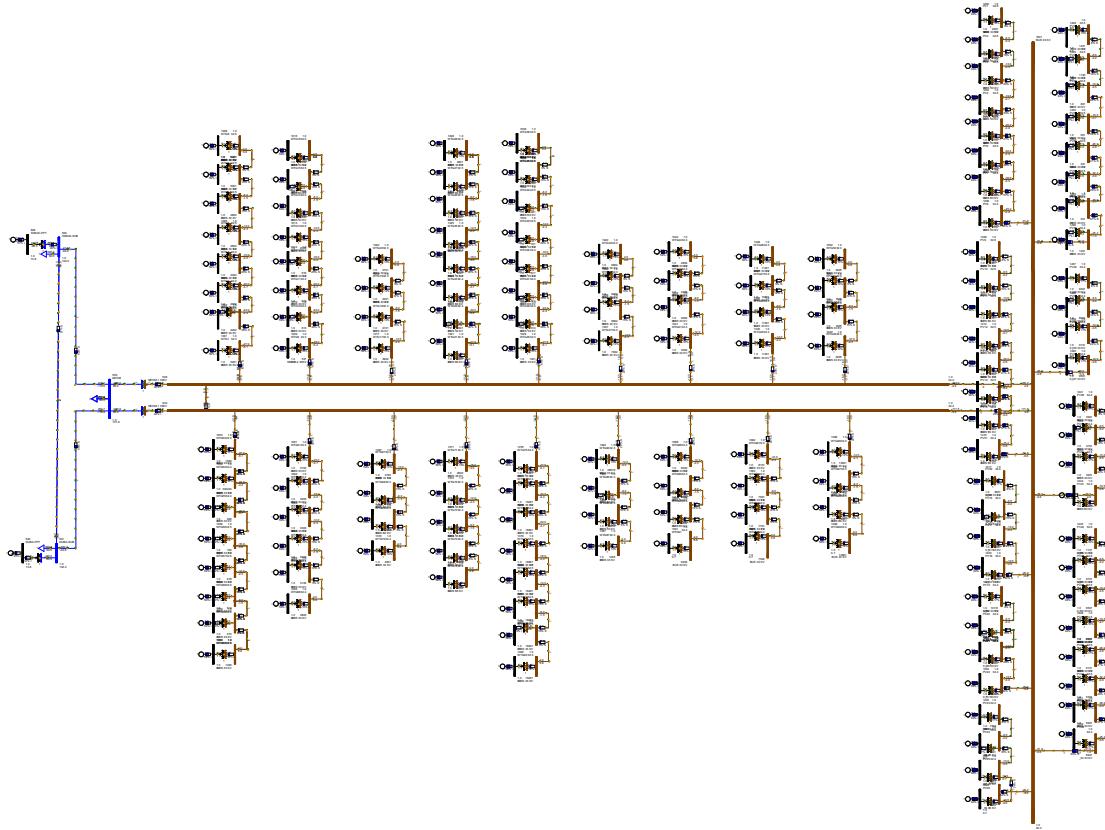
| RES      | Model Combination | Function                      | Model Name |
|----------|-------------------|-------------------------------|------------|
| Solar PV | regc_a            | RES Generator/Converter Model | REGCA1     |
|          | reec_a            | RES Electrical Controls Model | REECA1     |
|          | repc_a            | RES Plant Controls Model      | REPCA1     |

In this scenario also the aim is to investigate the compliance of synthetic Oxagon NEOM dynamic model connecting to the Saudi Arabia transmission grid with the SAGC, in which

the system performance is also compared to operating limits and criteria. This part will not be discussed in detail. All steps discussed in the previous part. The 33 kV solar PV plant bus is connected via two 33 KV power transmission bus bars with a wind farm. Figure 4.9 shows the connection of the 650 MW Synthetic Oxagon NEOM dynamic model projects to the transmission grid. In addition, the aggregated synthetic model of the 650 MW Oxagon NEOM dynamic model is connected to the transmission grid, as shown in Figure 4.10.



**Figure 4.9:** Connection of the 650 MW a Synthetic Oxagon NEOM Dynamic Model projects to the transmission grid.



1

**Figure 4.10:** Aggregated synthetic model of 650 MW Oxagon NEOM dynamic model connected to the transmission grid.

## Simulation and Results

Since the results of the standalone wind farm in the first scenario have been done, the previous results will be compared with the results of the second scenario. Figure 4.11 shows the angular response of the conventional generator rotor (TABUK-PPT) and (DUBA-PPT) during integrated solar PV with the standalone wind farm. It can be seen that there is no significant impact on conventional generators, which remain synchronized. The standalone wind farm exhibits more significant initial angular deviations, slower damping of oscillations, and a longer settling time, reflecting its dependence on variable wind energy alone. In contrast, integration of solar PV energy improves the response of the system by reducing the amplitude of deviations, improving damping, and achieving stability faster.

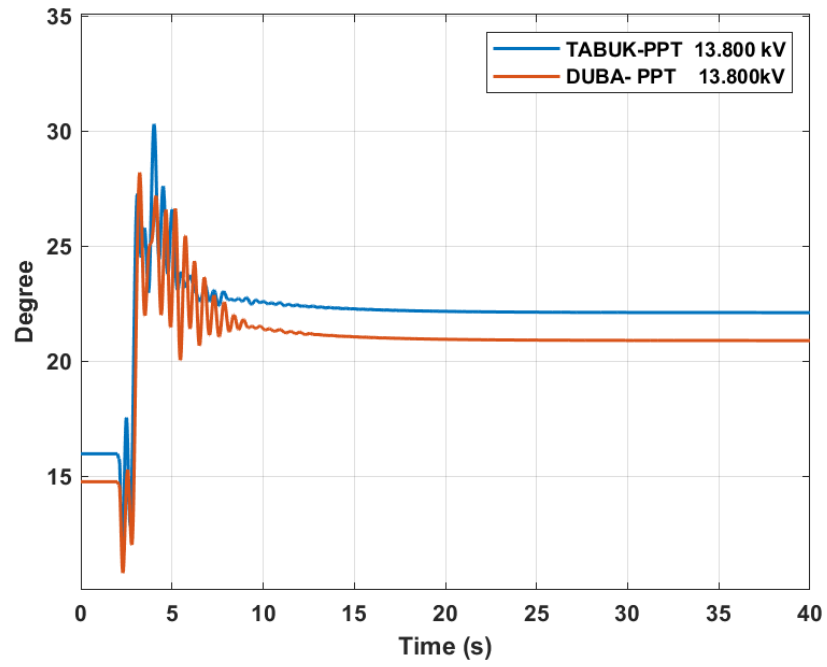
Figure 4.12 illustrates the frequency transient response of the system after a fault occurs in the 132 kV during the second scenario, it can be seen that the initial frequency deviation approximately reaches 0.0025 pu, compared to the standalone wind farm, which shows a slightly higher initial deviation but stabilizes faster. The frequency deviation in the standalone wind farm takes around 15-20 seconds to settle to a steady state. In solar PV with integrated wind farm system, stability is achieved in 5-10 seconds. Thus, the dynamic stability of a solar PV system demonstrates improved dynamic stability, with faster damping and reduced frequency variations.

During the active power response for two selected units, WTG 5 and WTG 99, in the second scenario, as the figure 4.13 shows, there is a sharp decrease in active power immediately following the fault. This phenomenon is caused by the magnitude of the drop

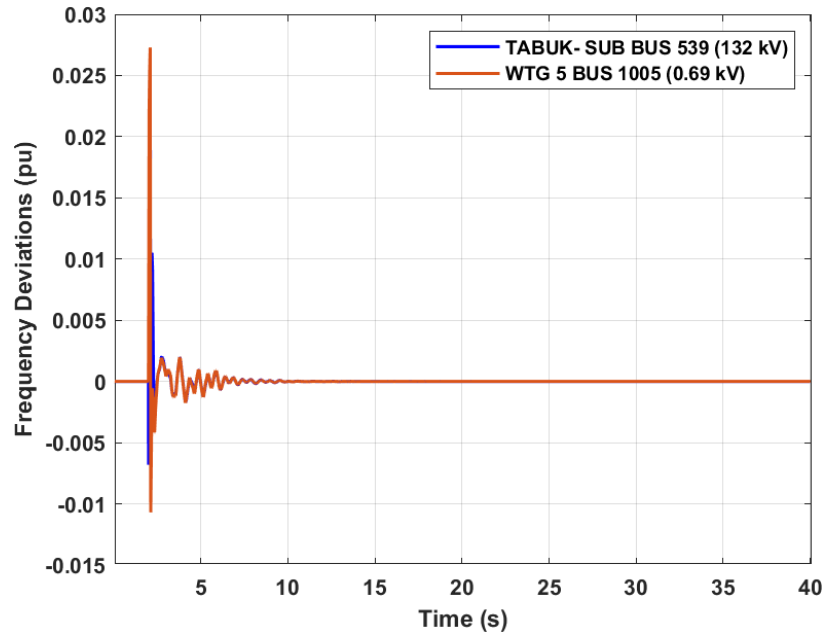
in active power. Thus, compared to a standalone wind farm, active power recovers faster. In contrast, with adding solar PV that means that shared power generation leads to higher steady-state power levels and smoother recovery.

Figure 4.14 demonstrates the reactive power response of a wind farm integrated with Solar PV. Compared to the first senior, both responses exhibit a sharp spike in reactive power immediately following the fault. However, the standalone wind farm shows pronounced and sustained oscillations in reactive power, which gradually settle over time. The Solar PV with wind farm that represents the second senior demonstrates a higher steady-state reactive power, faster stabilization, and better damping of oscillations compared to the stand-alone wind farm. In addition, Figure 4.15 shows the behavior of wind turbines in response to a disturbance during a fault in a wind farm with the integration of solar PV.

According to the results, after comparing the two seniors of the standalone wind farm and the integration of solar PV with the wind farm, it can be observed that the integration of solar PV with the wind farm improves the damping of oscillations by providing a secondary energy source and stabilizing the active power grid. This reduces the oscillation amplitude in the rotor speed and enhances damping. This improvement refers to the capabilities of combining systems, which are the benefits of combining renewable energy sources for more robust and efficient power systems. Therefore, based on the results, the integration of 650 MW of solar PV with wind farms does not have a negative impact on the security and reliability of the transmission system.

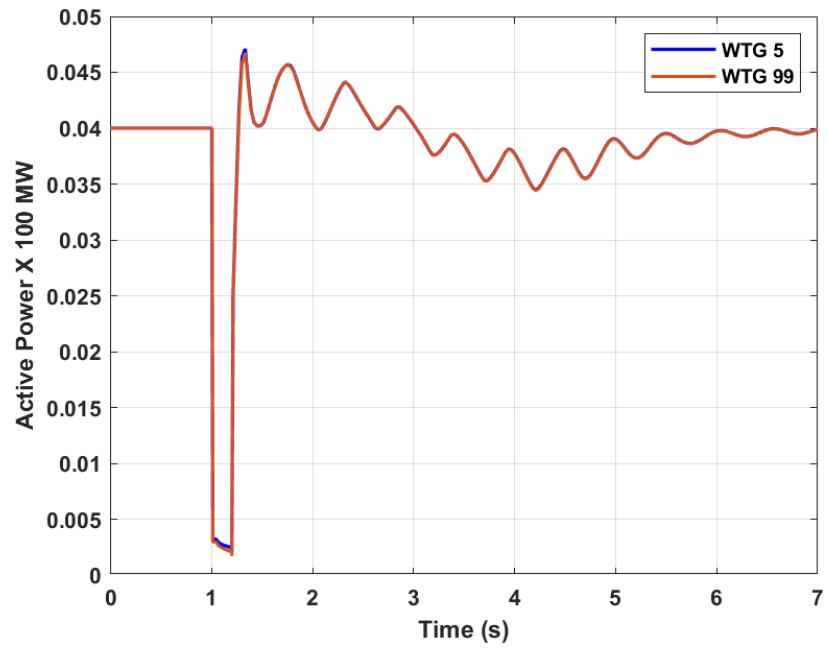


**Figure 4.11:** Rotor angular transient response of conventional generators during a fault in a wind farm with Solar PV integration.

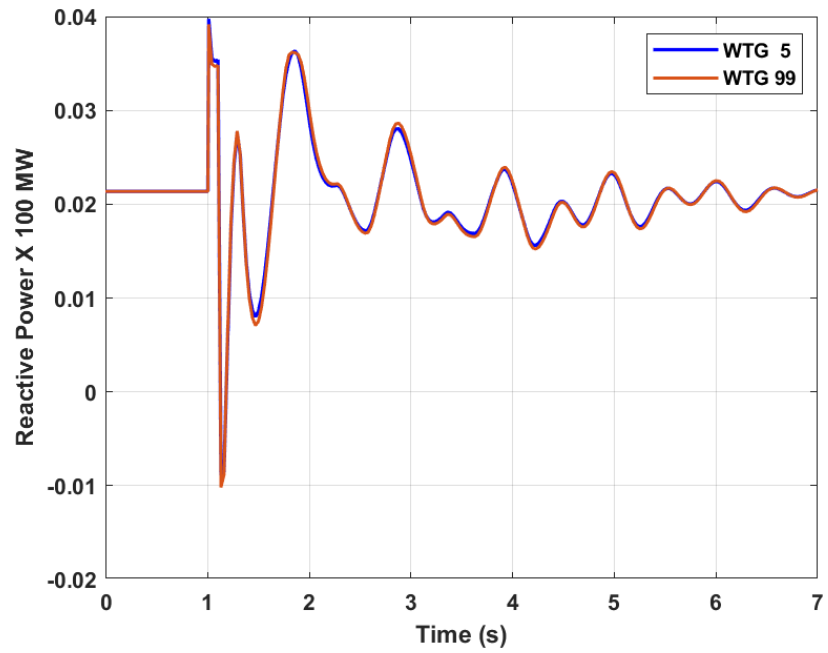


**Figure 4.12:** Frequency transient response after fault in the wind farm with Solar PV integration

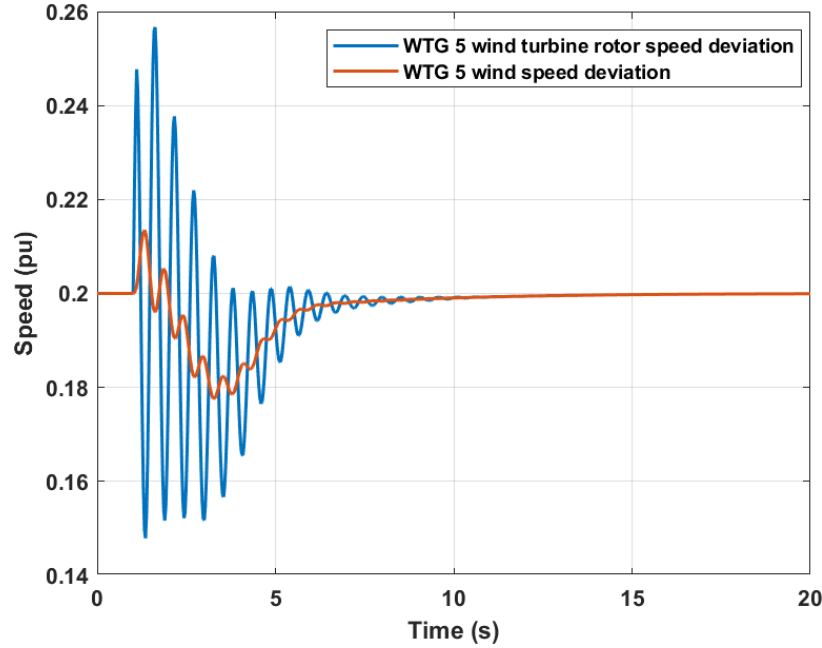




**Figure 4.13:** WTG active power response for two selected units WTG 5 and WTG 99



**Figure 4.14:** WTG Reactive power response for two selected units WTG 5 and WTG 99



**Figure 4.15:** Wind turbine speed and generator speed response

### 4.6.3 Assessment of Fault Ride Through Capability in the Saudi Arabian Grid Code

#### Reviewing the Fault Ride Through Ability of Saudi Arabian Grid Code Fault Ride-Through (FRT)

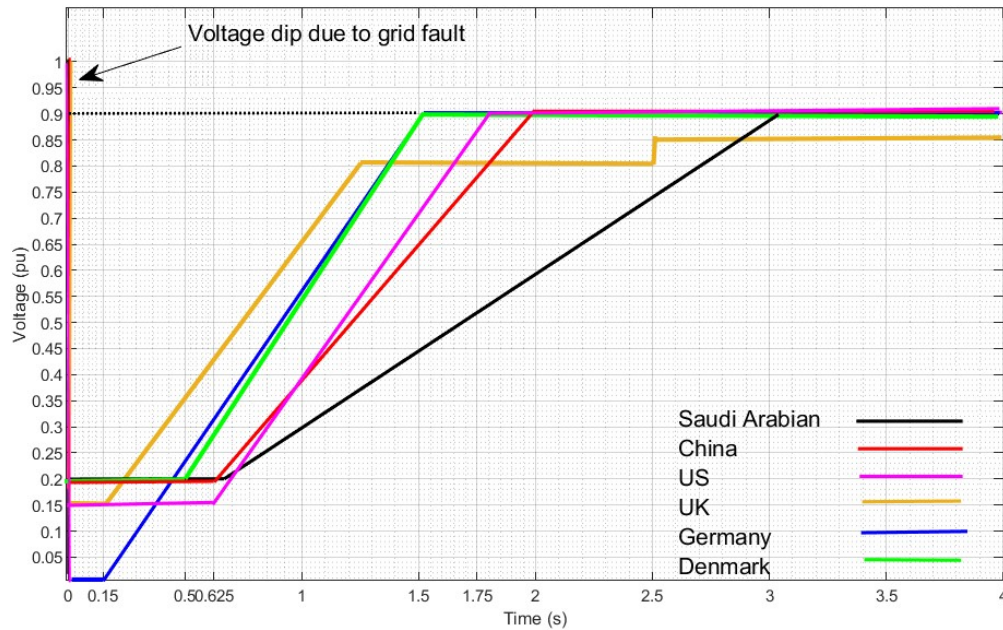
Short circuits and rapid changes in sources and loads cause a voltage magnitude change that can last several seconds. Considered a fault occurrence when the fault percentage is too high, distributed generation based on inverters may be disconnected from the electric power grid according to the IEEE 1547-2018 standards (93). LVRT (Low Voltage Ride Through) and HVRT (High Voltage Ride Through), both also known as FRT - Fault Ride Through (11). Low voltage ride-through (LVRT) is the ability of Distributed Generation (DG) to ride through a significant voltage drop at the POC and remain connected to the grid for some

time before the fault is cleared (97). In these scenarios, both wind and solar PV converters must remain synchronized to energize the power system. Although most transmission system operators have similar grid codes for wind and PV systems, the different characteristics of their systems lead to differences. Thus, (L / HVRT) helps ensure the balance of the power system and maintain a stable frequency during and after disturbances (1).

Denmark, the UK and Germany have the most developed integrated wind power systems between renewable energy countries, while the UK, Germany, the United States and China produce the most wind energy (98). Since the Saudi grid is set to integrate wind power in the future. Therefore, this section thoroughly reviews the voltage dip duration profile with LVRT requirements for large-scale wind farm integration in these countries using grid codes of the UK National Grid (99), Germany (100), Denmark Energinet (101), China GB/T and NB/T (102), USA ERCOT (103), and Saudi Arabia Grid Code (29) as illustrated in Figure 4.16.

Saudi Arabia and China fault ride-through requirements are similar to the Denmark grid code and are determined with respect to the drop down to 20%, but not sufficient for faults very close to the POC where the voltage can drop down to 0%. Germany and the United Kingdom have the lowest short-circuit time duration with only 150 ms. However, the UK grid code requires that the wind turbine remain connected to the electrical grid during the drop 15%, while the German grid code requires that wind power installations remain connected during the drop in voltage to 0%. The German grid code and the draft connection code ENTSO / E require wind power installations to remain connected during a voltage drop down to 0% from the rated voltage in the POC for a duration of 150 msec, where (ENTSO / E)

refers to the European Network of Transmission System Operators for Electricity that covers all EU countries that are part of the European Energy Union such as Norway, Switzerland, Turkey, and Albania. Each power system of a country is characterized with different structure and behavior such as grid configuration, system voltage levels, short circuit current levels, transient stability margin, voltage stability margin, relay system protection setting, etc. Therefore, deciding on proper fault ride-through requirements is not an easy task (104). US has several requirements, but the common order No. 661 requires WPPs to have LVRT capability down to 15% of the rated line voltage for 0.625 s (103). In general requirements for all codes, all plants must also be able to operate continuously at 90% of the rated line voltage, measured on the high voltage side.



**Figure 4.16:** Comparing LVRT regarding fault ride through capability of National Grid Codes.

To make comparisons between LVRT requirements in different countries, it is essential to thoroughly understand the specificity of each grid code, including how they determine and measure LVRT performance, which can cause challenges when trying to compare them directly. In general, the differences are due to various factors according to (104; 105):

- Grid infrastructure and stability systems.
- Renewable energy penetration.
- Technical standards, practices, protection, and control such as total fault clearing time targets.
- Post-fault voltage recovery (duration and level), which depends directly on the relay protection and high-voltage circuit breaker technology installed in each national power system.

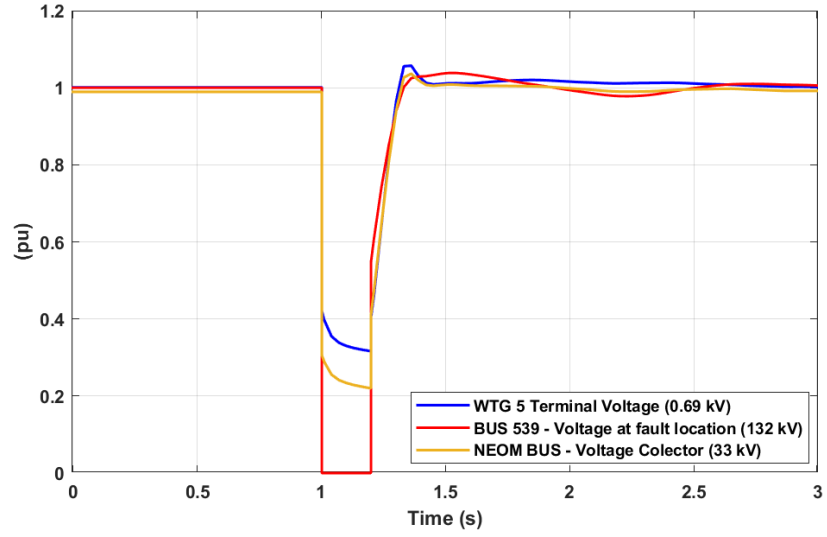
### **Voltage Response-Fault Ride through Ability**

A wind farm power system may experience different types of fault. As mentioned previously (L/HVRT) standards mean the ability of inverter-based distributed generation to ride through a significant voltage drop at the POC and remain connected to the grid for some time before the fault is cleared. A simulation for two scenarios has been performed to evaluate the low-voltage ride-through and the response of the first and second synthetic models to the Saudi grid code.

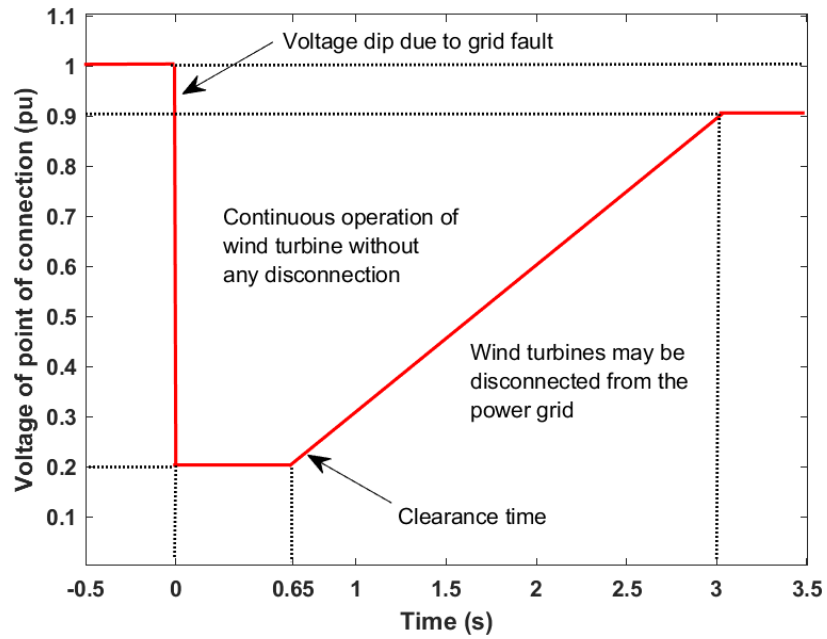
The three-phase symmetric fault is the only fault simulated in this section, as it frequently occurs on the 132 kV transmission line in the Saudi grid system. The faults that occur at the point of connection have been applied at three different locations.

Figure 4.17 shows that during the fault on the 132 kV connected line (near the POC), which is in the scenario of a synthetic model scenario of a standalone wind farm, the voltage at the 132 kV point of connection drops to zero. The WTG 5 terminal voltage shows a similar response, except that during the fault the minimum terminal voltage was 0.36 pu, which is considerably higher than the faulted connection point voltage 0.20 pu. As mentioned in DCC6.4.2 (29). This states the following (When the voltage at the POI drops to 20% of the rated voltage, the WTGs should ensure continuous operation without disconnection for 0.650 seconds. Similarly, when the voltage at the POI recovers to 90% of the rated voltage within 3 seconds after the voltage drops, the generators should ensure continuous operation without disconnect as shown in Figure 4.18.

The voltage drop on the 33 kV collector bus is 0.22 pu. After fault clearance, when the fault line is disconnected from the grid, the voltage at both locations (132 kV and 33 kV) recovers to around 0.97 pu. for approximately 0.13 sec. Corresponding to the technical requirements of the Saudi grid code regarding the fault ride through the simulation, the results indicate that all 100 WTGs have the ability to ride through the fault for the short circuit occurring near the POC.

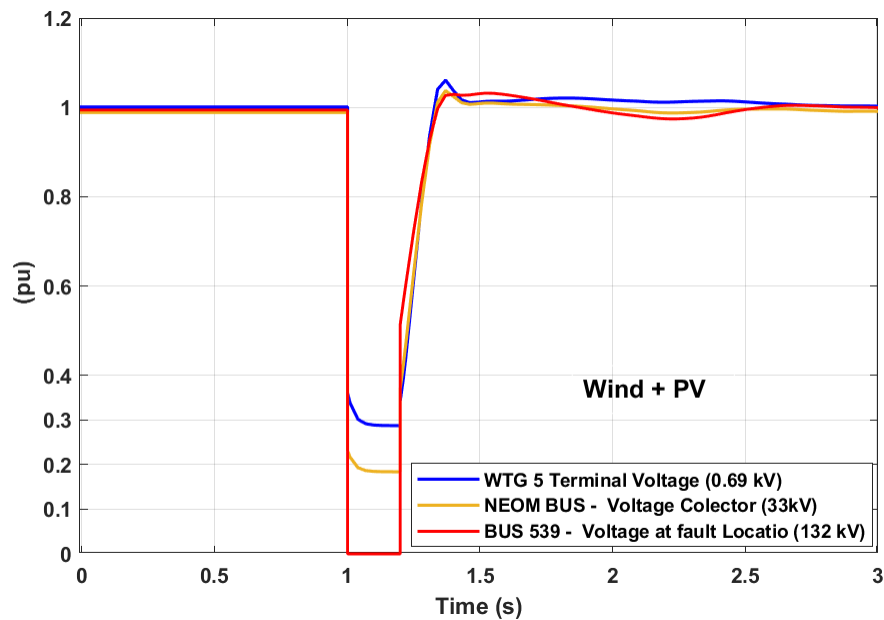


**Figure 4.17:** Voltage response after fault occurrence in the 132 kV connection line of the stand alone wind farm, highlighting Fault Ride Through performance.



**Figure 4.18:** Low Voltage Ride Through (LVRT) of Saudi Arabian Grid Code when voltage at the Point of connection (POC) drops.

Compared with the second scenario, Figure 4.19 shows the voltage response after the occurrence of the fault in the 132 kV connection line of solar PV with the wind farm, it is observed that the minimum voltage decreased from 0.36 pu when solar energy was added to the system to 0.29 pu. This reduction can be attributed to the inherent differences in the electronic components and control strategies employed by solar energy systems. Consequently, corresponding to the technical requirements from Saudi grid code regarding the fault ride through the simulation results indicate that adding solar PV with a wind farm has the ability to ride through the fault for the short circuit occurring near the (POC).



**Figure 4.19:** Voltage response after fault occurrence in the 132 kV connection line of the wind farm with Solar PV integration, highlighting Fault Ride Through performance.



## 4.7 Summary

- Detailed synthetic models of future wind energy resources have been created in Saudi Arabia.
- The integration of wind farms into the Saudi transmission grid was assessed to adapt the requirements of the grid code to accommodate wind turbine generators (WTG) and ensure system stability as wind power installation increases in the future.
- The potential of wind farms during grid failures was examined to assess their functionality in voltage drop and feedback within the grid. Moreover, to verify compliance with grid stability at a large scale.
- A comparison has been made between the evaluation of different technical approaches for a range of countries to achieve compliance with the LVRT.
- The simulation indicated that the wind farm meets most grid code requirements, including fault riding under certain conditions. However, with the integration of solar PV, the drop in voltage near the (POC) to below acceptable levels reveals the need for code improvement.
- There is a potential for developing these models with more accurate data in the future.

## Chapter 5

**IMPACT OF THE WIND**

**TURBINES PENETRATION ON**

**FREQUENCY STABILITY OF THE**

**SAUDI SYNTHETIC ELECTRIC**

**GRIDS**

## 5.1 Overview

This chapter explores the impact of wind turbine penetration on the frequency stability of Saudi electric grids, utilizing a synthetic grid model developed from open-source data and tailored to reflect the specific characteristics and operational requirements of the Saudi power system. The model, which commits to Saudi code and simulates the behavior of actual power grids, is hosted on the CURENT Large-scale Testbed (LTB) platform and serves educational, training, and research purposes. It specifically examines the transient response of the grid to severe disturbances, such as sudden loss of a major conventional generator, under-frequency load shedding, full wind penetration at one area by simulating different levels of wind turbine penetration, and their effect on frequency metrics. Furthermore, this assessment aims to identify the limits of renewable energy integration in each region and throughout the grid, which is increasingly important as the share of wind energy in the Saudi electricity grid increases.

## 5.2 Motivations

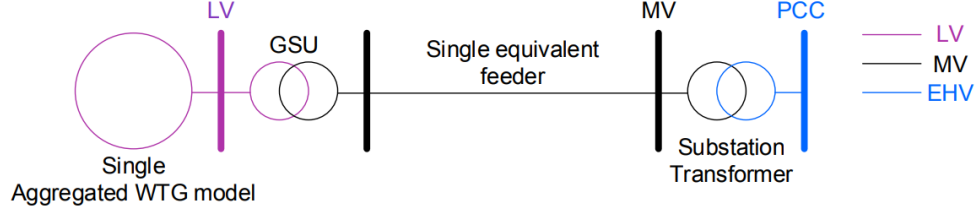
- Assessment of the reliability and stability of Saudi power grids in the face of the inherent fluctuation and variability of the integration of wind power challenges to maintaining frequency stability.

- Investigating the regulatory compliance and standards grid codes during the integration of wind turbines to ensure that new technologies can be perfectly integrated into existing grid structures.
- Study and assessment of the behavior of the Saudi power grid in response to disturbances, such as the loss of large conventional generators and scenarios of high wind power penetration.
- Creating and developing a synthetic model of the high-wind penetration scenarios model for educational and research purposes that accurately simulates real-world scenarios.

## 5.3 Wind Turbines Penetration in the Synthetic Saudi Electric Grid

### 5.3.1 Wind Power Modeling

For bulk power system stability analysis, the main concern is the dynamic behavior when increased wind turbines penetrate Saudi synthetic electric grids. The wind power farms is represented by a conventional generator and a transformer connected to the grid at the point of connection coupling (POC), as seen in Figure 5.1 (3).

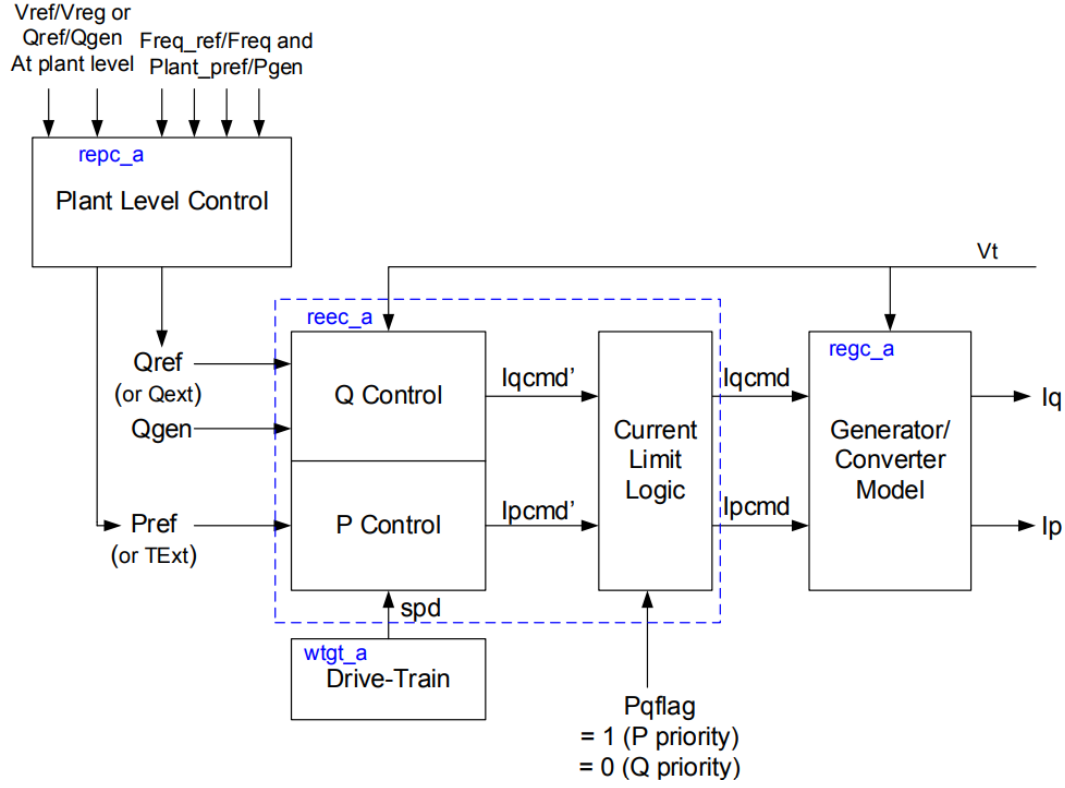


**Figure 5.1:** Simple aggregated model for a WTG power plant (3)

The dynamic performance of wind power farms is represented by the PSS/E group dynamic model reference generation type 4 WTG generic wind turbine dynamic model, which was used to simulate the performance of a wind turbine employing a generator connected to the grid via the power converter (Type 4) (47). Aggregated WT4 Plant Models (REGC\_A, REEC\_A, WTGT\_A, REPC\_A) These models are used to simulate a wind power farms as a single equivalent unit, suitable for large-scale studies (3).

The Type 4 WTG generation model is designed to be highly adaptable, making it suitable for various grid studies and integration scenarios (106). It can be used to simulate the behavior of aggregated wind farms (107). Type 4 WTGs use full-scale power converters to connect the wind turbine to the grid, (108).

The overall structure of the second generation type 4 WTG model has four parts, as shown in Figure 5.2. This comprehensive modeling approach ensures that the dynamic behavior of Type 4 WTG under various grid conditions is accurately represented, facilitating detailed studies on the impacts of wind turbine penetration on grid stability and performance. Table 5.1 shows the combination of models and the function of the second generation type 4 WTG aggregated model described below (106). The model functions and converter controls tasks are described in detail in (47; 3).



**Figure 5.2:** Block diagram for Generic Wind Turbine (Type-4 WTG ) (3)

**Table 5.1:** Model Generic Wind Turbine (Type-4 WTG ) aggregated model combination functions

| RES               | Model Combination | Function                      | Model Name |
|-------------------|-------------------|-------------------------------|------------|
| <b>Type 4 WTG</b> | regc_a            | RES Generator/Converter Model | REGCA1     |
|                   | reec_a            | RES Electrical Controls Model | REECA1     |
|                   | repc_a            | RES Plant Controls Model      | REPCA1     |
|                   | wtgt_a            | WTG Turbine Shaft Model       | WTDTA1     |

### 5.3.2 Wind Turbine Penetration Levels and Locations

Wind power farms locations should be strategically selected to ensure that each chosen site receives a sufficient average wind speed throughout the year and is located near load centers. According to previous studies, most of the areas in Saudi Arabia have significant potential for wind energy generation (66; 28; 69). This means that the five operational regions in the country are suitable for the installation of wind turbines.

As the wind penetration level increases, conventional generators in the Saudi synthetic electric grid model will be gradually replaced by wind power turbines. Since wind turbines operate efficiently at varying power factor values, conventional machines with higher power factors are given priority for replacement

According to the Saudi Arabian grid code (29), the frequency of the system must be maintained within the range of 59.9 and 60.1 Hz during regular operation. The allowable frequency range during a contingency is typically more comprehensive than during regular operation to accommodate the temporary imbalance between supply and demand, which occurs during a contingency of 59.5 to 60.5 Hz. Provided that frequency deviations are confined within these limits and the system remains stable after any disturbance. Thus, wind power turbines can be integrated into the Saudi synthetic electric grid model. This ensures that the stability and reliability of the Saudi power grid is respected.

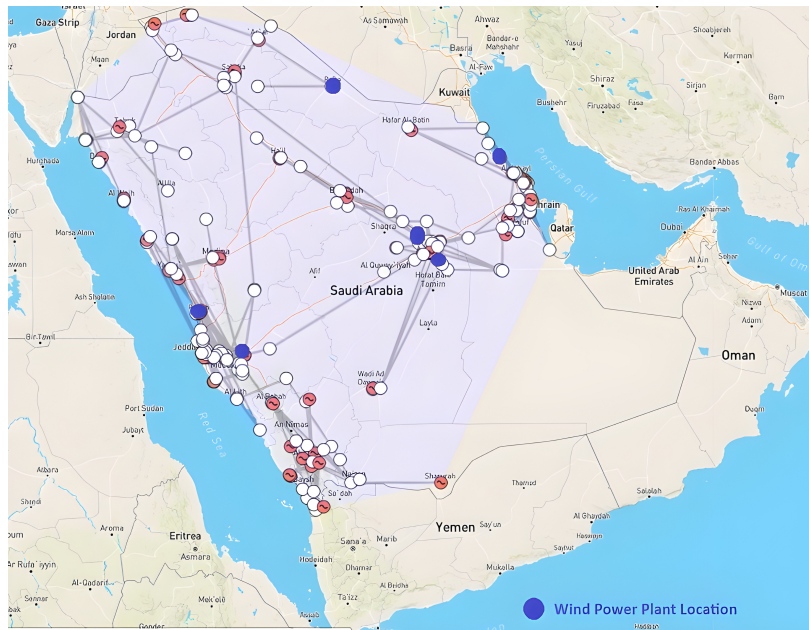
Wind power turbines are incrementally integrated into the system at penetration levels of 20%, 40%, 60%, and 75%. Exceeding a 75% penetration level with wind turbines leads to a loss of system stability. Figures 5.3 through 5.6 show the locations of the wind turbines

in Saudi synthetic power grids for each scenario using AGVis. The amounts of wind power generation for each penetration level are summarized in Table 5.2. Tables from 2 to 7 in the appendix describe in detail the generators replaced to accommodate the wind power turbines at all four penetration levels.

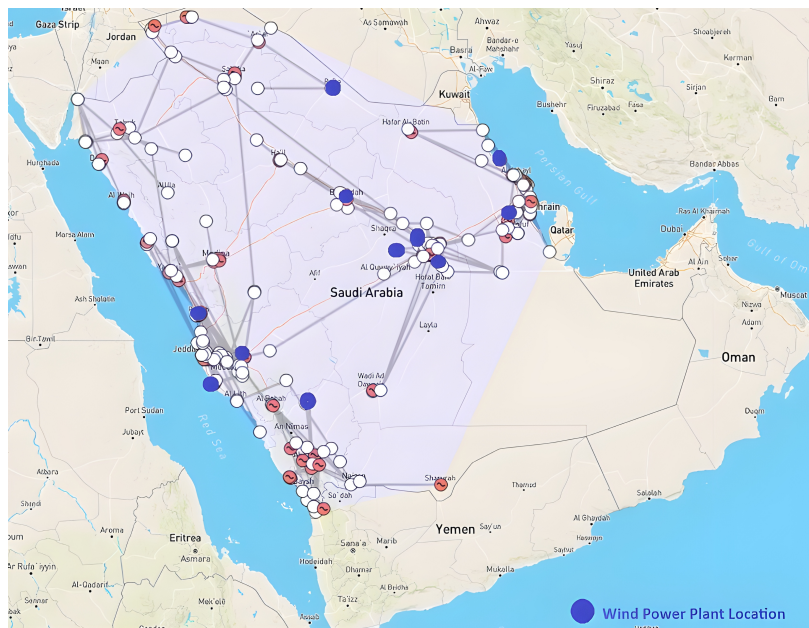
| <b>Total Generation</b> |                                                   | <b>64,674 (MW)</b>                         |
|-------------------------|---------------------------------------------------|--------------------------------------------|
| <b>Scenario</b>         | <b>Percentage of Wind Turbine Penetration (%)</b> | <b>Wind Turbine Actual Generation (MW)</b> |
| 1                       | 20%                                               | 12,934                                     |
| 2                       | 40%                                               | 25,869                                     |
| 3                       | 60%                                               | 38,804                                     |
| 4                       | 75%                                               | 48,505                                     |

**Table 5.2:** The wind power generation amounts for each penetration level





**Figure 5.3:** 20% wind power turbine penetration map



**Figure 5.4:** 40% wind power turbine penetration map

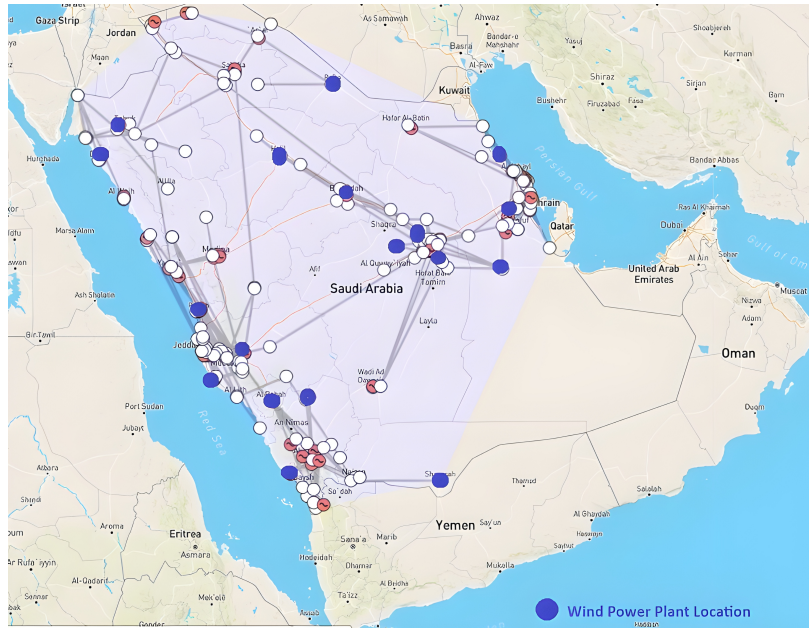


Figure 5.5: 60% wind power turbine penetration map

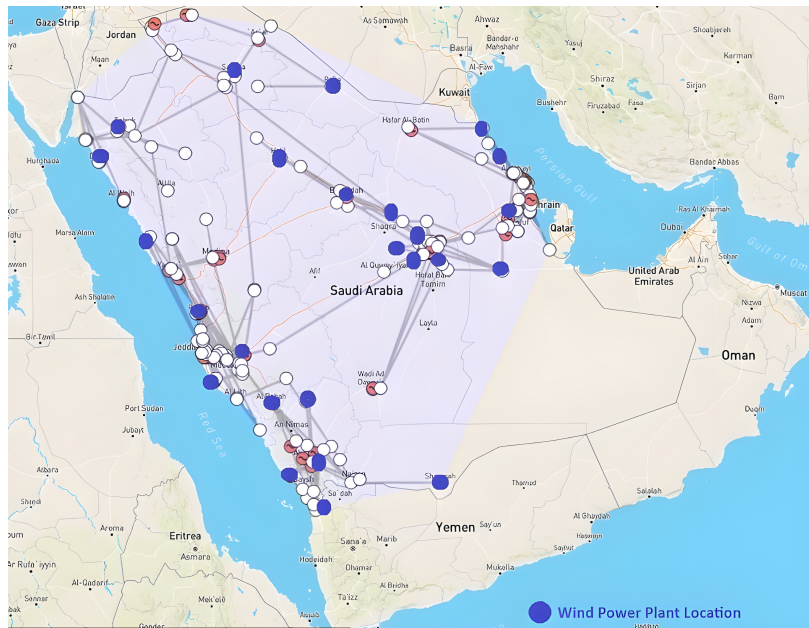
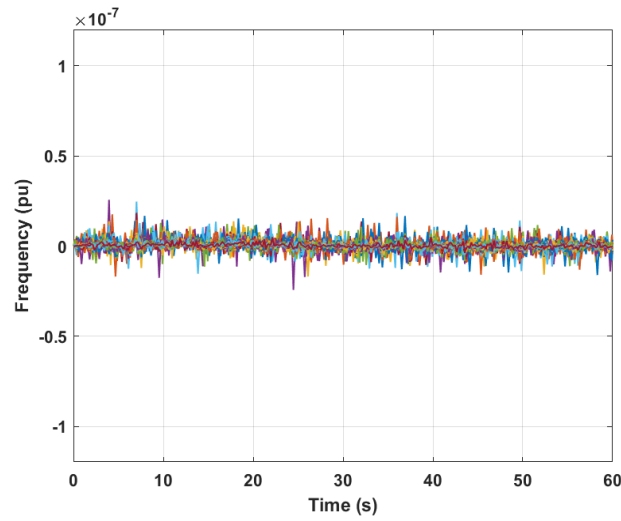


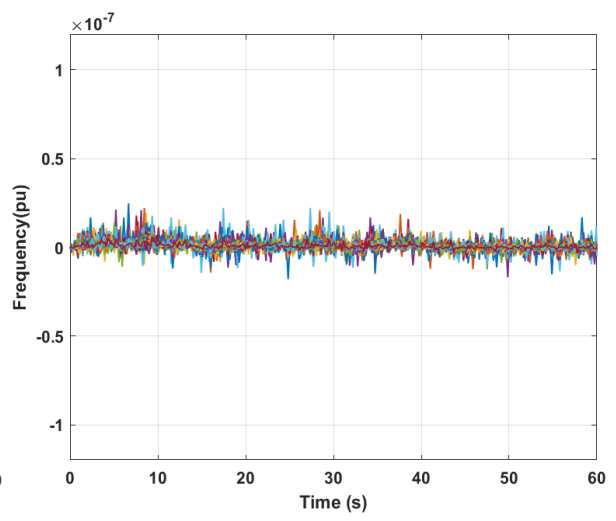
Figure 5.6: 75% wind power turbine penetration map

### 5.3.3 Simulation of a Flat Run with High Wind Turbine Penetration.

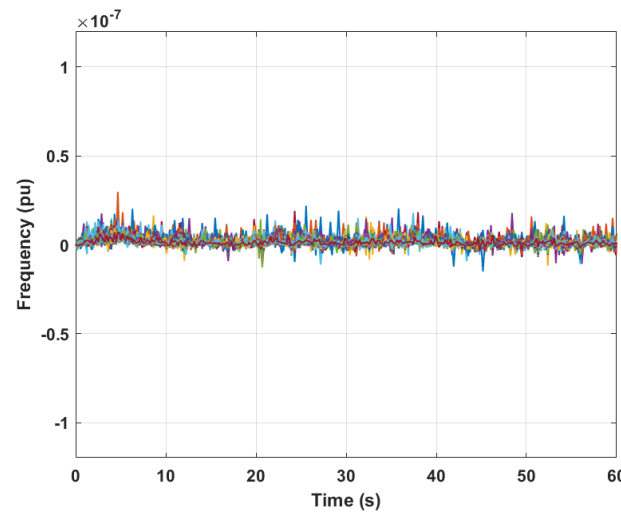
As mentioned earlier in Chapter 3, this disturbance-free "flat run" simulation is implemented to verify that dynamic models generate minimal or no transients (57). After integrating the dynamic wind turbine model into the synthetic Saudi electric grid, it is important to ensure the dynamic and numerical stability of the model, which confirms its ready for dynamic studies. To achieve this, a no-disturbance simulation lasting 60 seconds is conducted. This simulation is designed to verify the stability of the grid with the inclusion of wind energy. The frequency response results for all the proposed cases of wind turbine penetration are presented in Figure 5.7. The data show that the system dynamic simulations for all levels of wind turbine penetration converge with very minimal numerical oscillations.



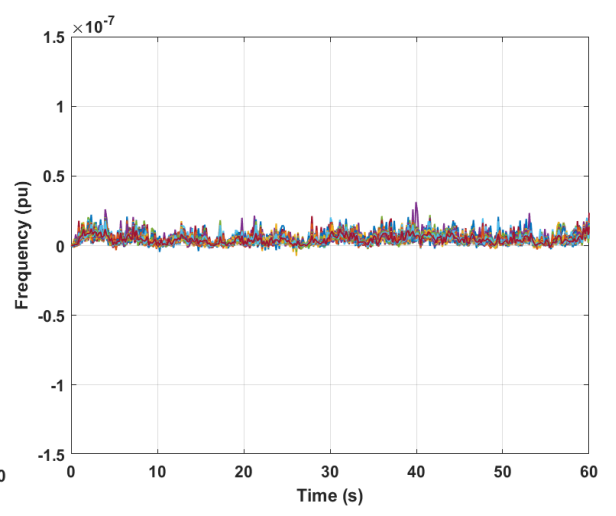
(a) 20% WTG Penetration



(b) 40% WTG Penetration



(c) 60% WTG Penetration



(d) 75% WTG Penetration

**Figure 5.7:** Frequency deviations in the Simulation of a Flat Run

## 5.4 Impact of High Wind turbine Penetration in the Synthetic Saudi Electric Grid on Frequency Response

As in Saudi Vision 2030, the Saudi power grid is undergoing significant transfer with the integration of renewable energy sources, particularly wind turbine units (4). This transition presents significant challenges for the frequency response of the grid, a critical aspect to ensure that the balance between power generation and demand is maintained throughout all regions of the Saudi power grid. Traditionally, synchronous machines, such as those in conventional thermal and steam power plants, have inherent inertia that provides immediate frequency support following disturbances, such as generator trips. This inertia helps mitigate frequency deviations by slowing the rate of change of frequency (91).

As the penetration of wind energy increases, the overall behavior of the inertial system changes, leading to rapid frequency deviations during disturbances (109). The dynamic characteristics of wind turbines mean that in the event of a disturbance, the frequency of the system can experience rapid changes and may change frequency behavior in electric grids, potentially compromising the stability of the entire grid (110).

This phenomenon requires a review of the ability of the grid to maintain stability and security under high penetration of wind turbines. In this section, a dynamic simulation is performed to observe how the system frequency behaves after different types of disturbance as more Wind turbine units are added to the grid.

### 5.4.1 Impact of a Conventional Generation Trip in Each Region

In this part, the behavior of each region was studied to examine the frequency response when a conventional machine is lost. It is commonly known that, depending on the amount of power it generates and where it is located within the grid, losing a conventional machine impacts the stability of the system (91). However, high penetration of wind turbines into the grid may cause the effects of losing synchronous generators, potentially causing instability between regions and affecting the power grid (111).

This study examines the impact of the sudden loss of a large conventional machine in three different regions, including the integration of wind turbine units. Simulate scenarios in the western, central and eastern operating regions of the Saudi grid to assess these dynamics. These regions were chosen because of their significant size in the Synthetic Saudi Power Grid, both geographically and as a load size. This analysis illustrates how regional variations in generation sources and grid integration impact frequency response and overall grid stability.

The three figures 5.8 5.9 5.10 respectively show a simulation of the disturbance of three generators in three different locations, as well as Table 5.3 showing a summary of the generation plants data for trips in the simulation in each region. In the central operating region, the simulation includes the trip of the largest generating unit located on the Riyadh Bus 352, which generates 1882 MW. The frequency response is measured on the Riyadh Bus 302. The basic case without wind penetration, 20%, and 40%, shows the least impact, maintaining the frequency above 59.5 Hz. With increasing levels of wind penetration, the frequency drops more clearly and fluctuation becomes apparent. At 60% and 75%

wind penetration, the frequency drops below the (UFLS) position, potentially causing load shedding mechanisms to stabilize the grid.

However, in the Eastern operating region, the tripped was in the generating unit on the Jubail Bus 201, which generates 1,608 MW. The frequency response is measured on Ras Tanura bus 205. When the generating unit tripped, the frequency of the system shows a sharp decline. As wind penetration increases, the initial frequency drop becomes more pronounced, with wind penetration 75% showing a significant frequency drop below the UFLS threshold.

In the Western operating region, the largest generating unit at Jeddah South Bus 117, producing 1610 MW, is tripped. The frequency response is observed at Bus109. With no wind penetration and penetration up to 65%, the frequency remains relatively stable, above 59.5 Hz. However, as the penetration of the wind increases, the frequency drop increases, and the oscillations become more obvious. At 75% wind penetration, the frequency drops below the UFLS position.

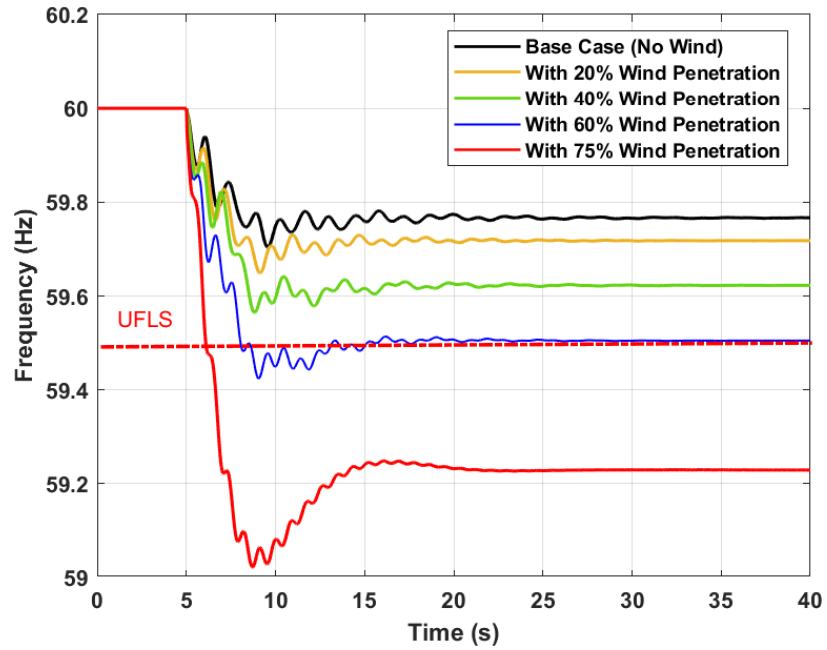
In comparison, the frequency response across the central, eastern, and western operating regions shows varying levels of grid stability in response to high-wind penetration. This is due to the varying number of loads and the power generation. In the central region, the disruption of the 1,882 MW led to a drop in frequency below 59.1 Hz, with severe oscillations and activation of UFLS in the penetration of 60% and 75%, highlighting significant stability challenges. Furthermore, in the (EOR), the disruption of the 1,608 MW unit on the Jubail Bus 201 results in a sharp drop in frequency, with increased wind penetration causing the frequency to drop below the UFLS limit at 59.39. The (WOR) shows the most pronounced



frequency oscillations and instability in the 75% penetration of the wind after the trip of the 1610 MW unit on the South Jeddah Bus 117. Thus, this scenario indicates that higher levels of wind penetration led to increased frequency instability after the generation trip, highlighting the need for improved grid support measures to deal with such disturbances and prevent cascading instability.

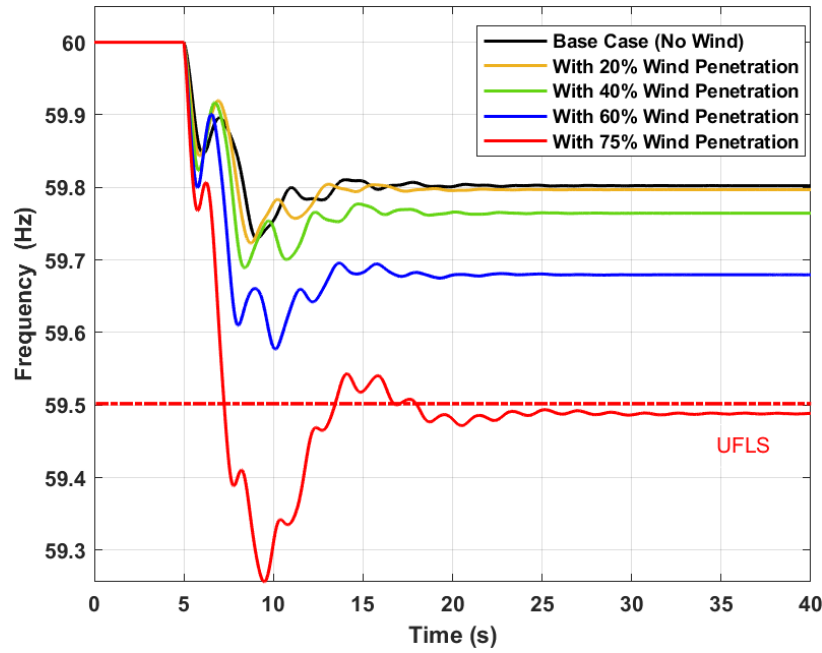
**Table 5.3:** Summary of Generation Plant Tripping Events and Frequency Responses

| Region | Tripping Bus     | Tripped Power (MW) | Frequency Response Bus |
|--------|------------------|--------------------|------------------------|
| COR    | Riyadh (Bus 309) | 1,882              | Riyadh (Bus 302)       |
| EOR    | Jubail (Bus 201) | 1,608              | Rastanura (Bus 205)    |
| WOR    | Jeddah (Bus 117) | 1,610              | Jeddah (Bus 109)       |

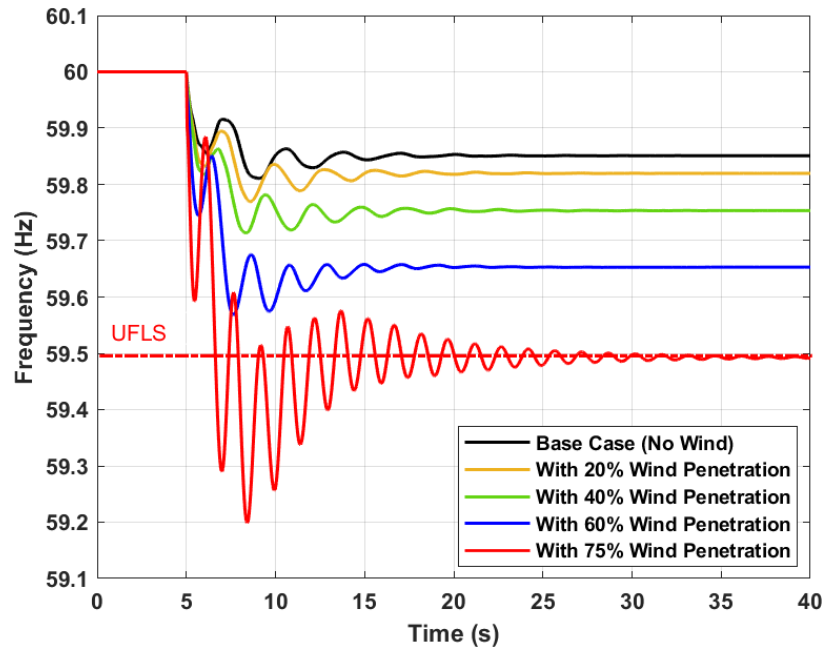


**Figure 5.8:** Frequency response with different wind turbine levels penetration following an event in the COR at (Bus 309) 1882 MW





**Figure 5.9:** Frequency response with different wind turbine levels penetration following an event in the EOR region at (Bus 201) 1608 MW.



**Figure 5.10:** Frequency response with different wind turbine levels penetration following an event in the WOR at (Bus 117) 1610 MW.

### 5.4.2 Impact on Frequency Response Metrics

The frequency of the power system is a key measure of grid stability. Consequently, frequency measurements are critical to monitoring the primary frequency response and ensuring stable system operation after disturbances such as generator failure (91).

This section evaluates the impact of the trip of a synchronous generator on frequency measurements, particularly with the increasing use of wind turbines in the Saudi power system.

Rate of change of frequency (ROCOF) refers to the speed at which the system frequency changes over time, always measured in hertz per second (Hz/s). It is a significant measure in power systems because it indicates the stability of the system and its ability to respond to sudden changes, such as loss of generation or load (112).

The frequency nadir is the lowest point at which the system frequency is reached after a disturbance, measured in hertz (Hz), reflects the ability of the system to withstand an imbalance between supply and demand. The lowest point may cause low frequency load shedding (113).

The frequency nadir time is the time it takes for the frequency to reach its lowest point, measured in seconds (s). This measure provides insight into the speed of the system response mechanisms(114).

Finally, the settling frequency is the stable frequency reached after the system recovers from the disturbance, measured in hertz (Hz). It highlights the effectiveness of secondary frequency controls in restoring the frequency to acceptable operating ranges (113).

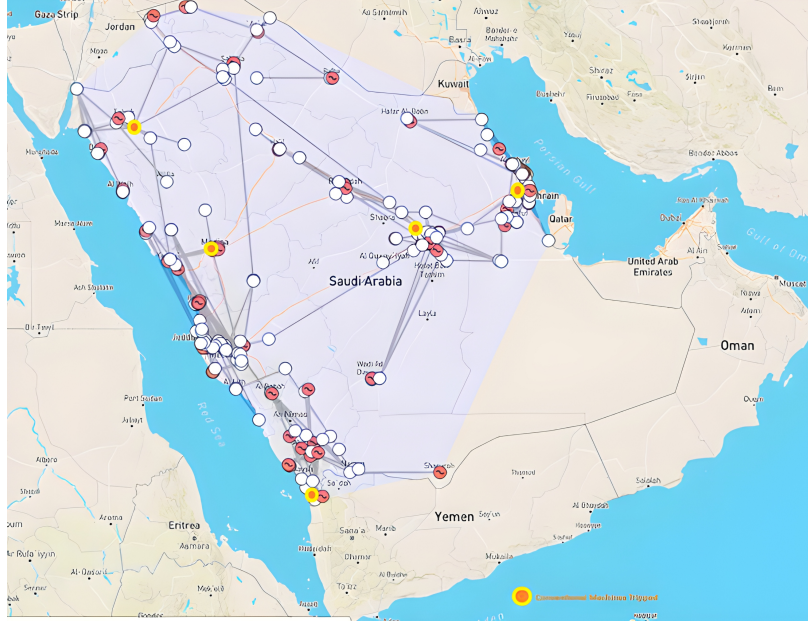
Frequency metrics are critical tools used in power system studies to assess the stability, reliability, and ability of the electric grid. They provide data on how fast the system responds to changes or disturbances, such as sudden loss of a large generator or significant change in load (91).

This study is particularly relevant since the Saudi power system is undergoing significant transformation, transitioning from traditional energy sources to a more diverse and sustainable energy.

A simulation is conducted to evaluate the effects of increased wind turbine usage on specific metrics, where a generator or a group of generators fell located in different areas in the Saudi synthetic electric grid, as shown in Figure 5.11. This simulation involves tripping generators producing between 800 and 900 MW in each operation region. Table 5.4 shows the name of the generator bus tripped and the amount of power generation tripped while testing different levels of wind power penetration and frequency metrics.

**Table 5.4:** Summary of Generation Plant Tripping Events and Frequency Responses

| Region | Tripping Bus      | Tripped Power (MW) | Frequency Response Bus |
|--------|-------------------|--------------------|------------------------|
| COR    | RIYADH (Bus 300)  | 982                | RIYADH (Bus 302)       |
| EOR    | ARAMCO (Bus 209)  | 808                | SALWA (Bus 222)        |
| WOR    | MADINAH (Bus 111) | 855                | KHAIBAR (Bus 109)      |
| NOR    | TABUK (Bus 538)   | 879                | NEOM (Bus 535)         |
| SOR    | SHUQAIQ (Bus 413) | 851                | SHUQAIQ (Bus 413)      |



**Figure 5.11:** Locations of generators tripped at different regions in the SSEG for Frequency Metrics

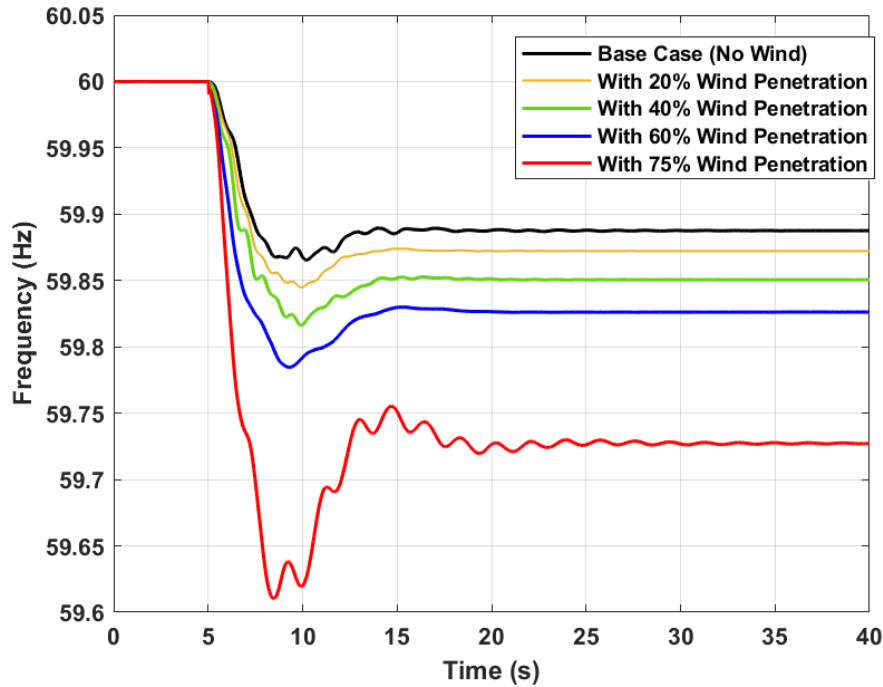
Figures 5.12 through 5.16 show frequency responses during 40 seconds when conventional machines tripped in each of the five regions (COR, EOR, WOR, NOR, and SOR). Frequency responses in power systems can differ significantly across different regions due to differences in grid topology, amount of generation, and load capacity. Each region operates with unique infrastructure, where regional topologies such as interconnections between generation plants, transmission lines, and load centers affect the way the system responds to frequency deviations.

For example, Figure 5.13 shows that heavily populated areas such as the Western Region during penetration 75% may have slower frequency responses and more fluctuation due to the longer transmission distance to send power fast. However, the Eastern region, as Figure 5.14 shows, with a high density of distributed generation or renewable energy sources, may

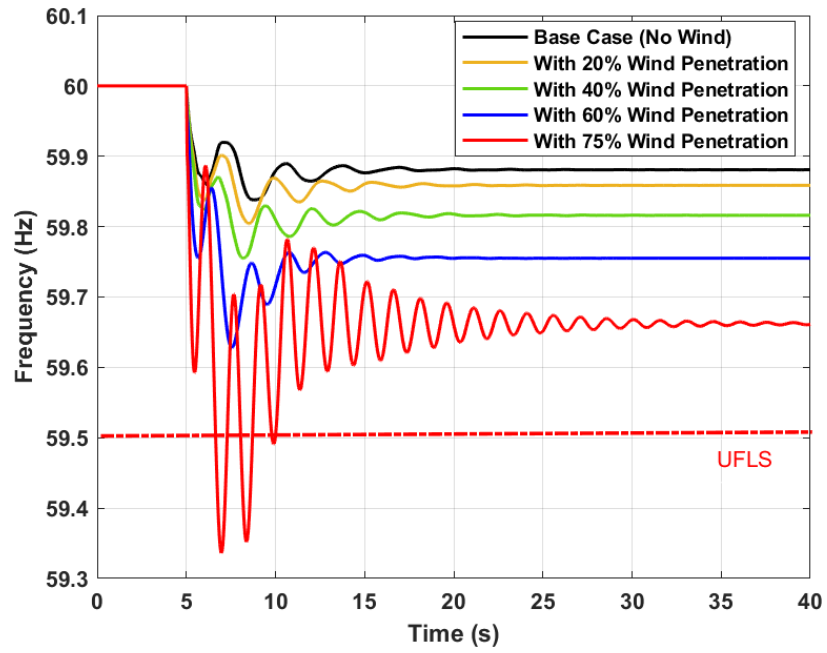
experience faster frequency responses because this region has a high amount of resources output to balance supply and demand.

Figures 5.15 and 5.16 show the frequency responses of the Northern and Southern regions. As can be seen, this region was not significantly affected, even when the penetration of the wind turbine reaches 75%. This is because these regions do not have highly populated or industrial areas.

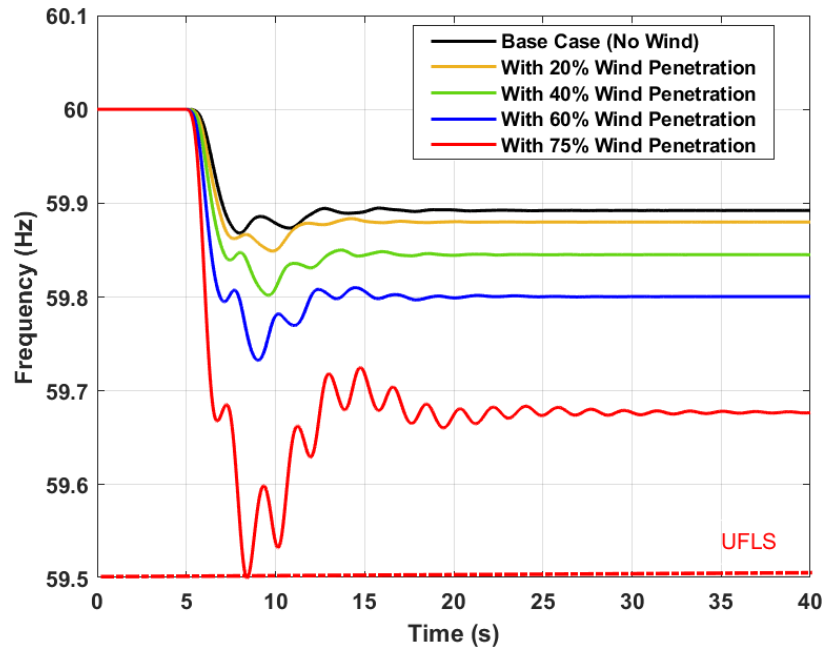
These differences in topology play an important role in determining how fast and effectively a region can return to a stable frequency after a disturbance. Therefore, the amount of tripped generation and the size of the load capacity are critical factors that influence the frequency response.



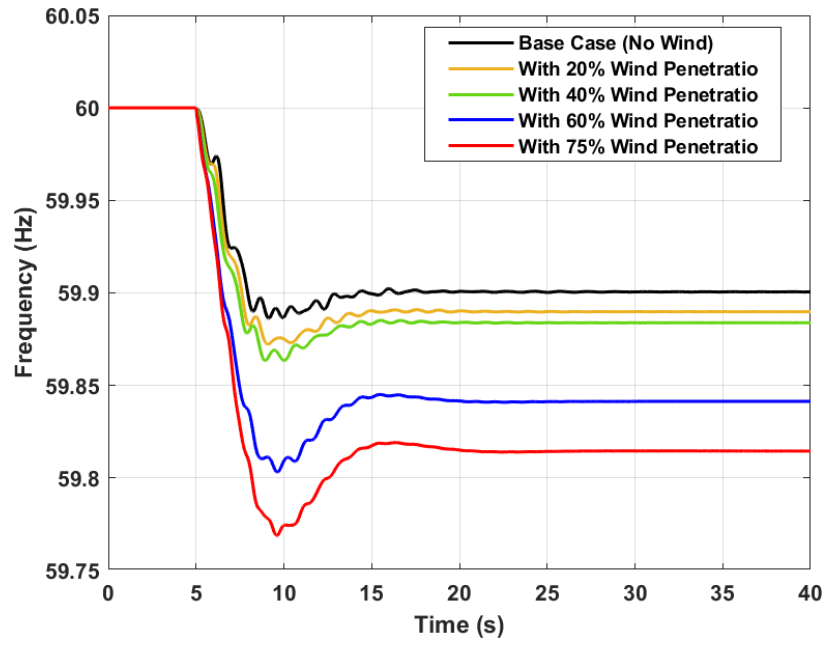
**Figure 5.12:** Frequency responses with different wind turbine levels penetration following an event in the COR Region.



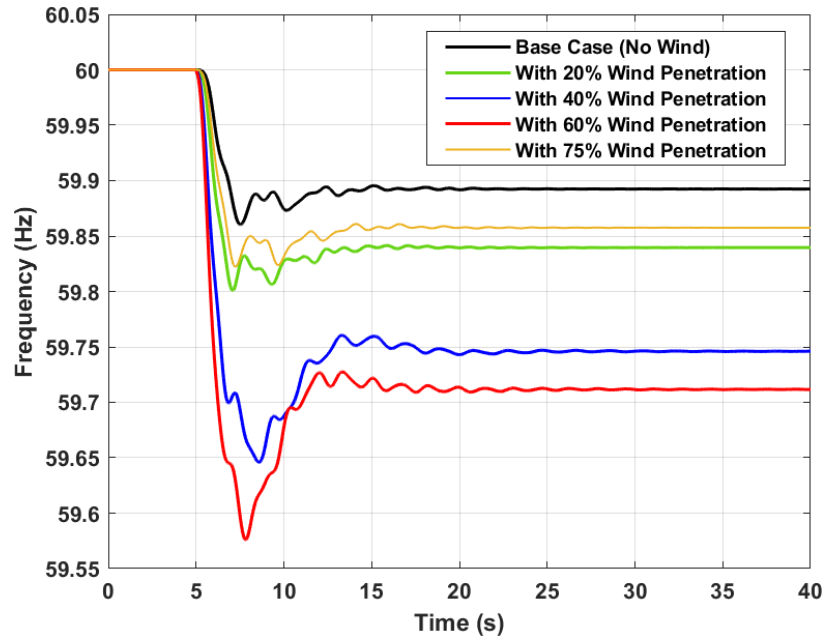
**Figure 5.13:** Frequency responses with different wind turbine levels penetration following an event in the WOR Region.



**Figure 5.14:** Frequency responses with different wind turbine levels penetration following an event in the EOR Region.



**Figure 5.15:** Frequency responses with different wind turbine levels penetration following an event in the NOR Region.



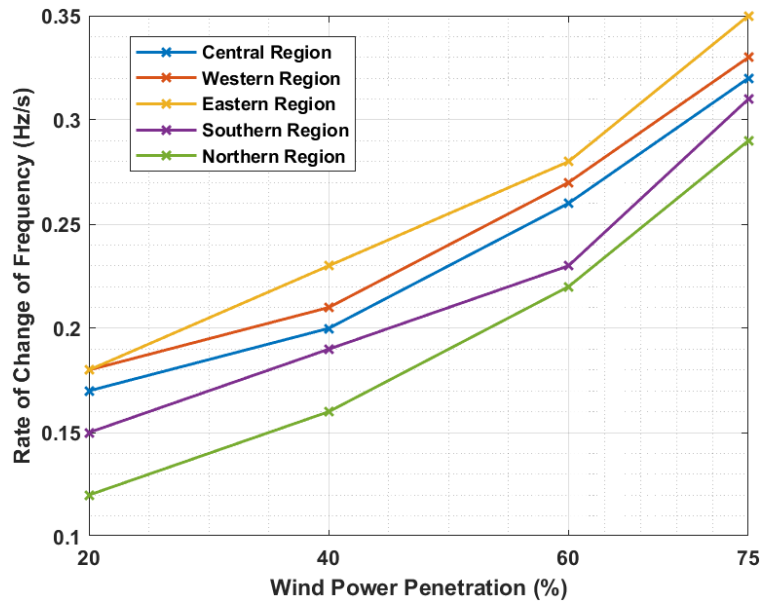
**Figure 5.16:** Frequency responses with different wind turbine levels penetration following an event in the SOR Region.

Figures 5.17 through 5.21 illustrate the five frequency response metrics for each of the five events in each operating region under different scenarios. As wind power penetration increases, the (ROCOF) shows a significant increase, which remains below the 0.36 Hz/s limit. Figure 5.17 illustrates that as the penetration of wind power increases, the ROCOF also increases in all regions, with the western region experiencing the highest ROCOF and the Northern Region the lowest at each level of penetration of wind power. According to the Saudi grid code, the allowed ROCOF limit is typically 0.5 Hz/s. This means that the frequency change should not exceed 0.5 Hz per second under normal operating conditions in response to sudden generation losses or disturbances (29).

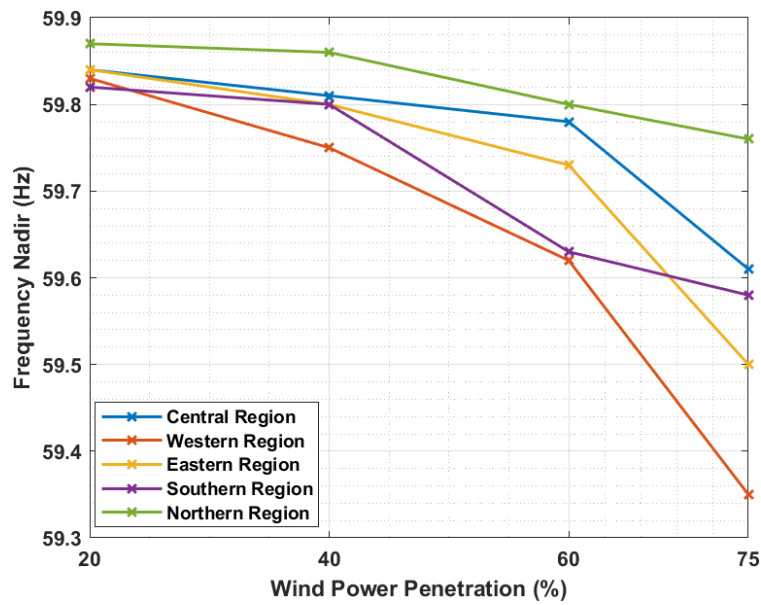
Figure 5.18 shows that the frequency of the nadir ranges from 59.3 to 59.9 Hz, during the penetration of wind power, ranging from 20% to 75%. In addition, the western region shows the most significant decrease in frequency nadir as wind power penetration increases, while the northern region shows the least significant decrease. Thus, the lowest point can lead to under-frequency load shedding. However, the reduction in the nadir time, shown in Figure 5.19, indicates a significant decrease. This suggests that while the frequency response changes only slightly, the speed at which it reaches its lowest point increases with higher wind power penetration. The Western Region experiences the largest decrease in nadir time. Furthermore, the data detect that the increase in the penetration levels of wind power results in a decrease in the settle frequency due to loss of generation, as observed in Figure 5.20. At a 20% wind power level, the settling frequency reaches between 59.87 Hz and 59.85 Hz, which drops between 59.83 Hz and 59.66 Hz at a 75% . Figure 5.21 indicates that as the



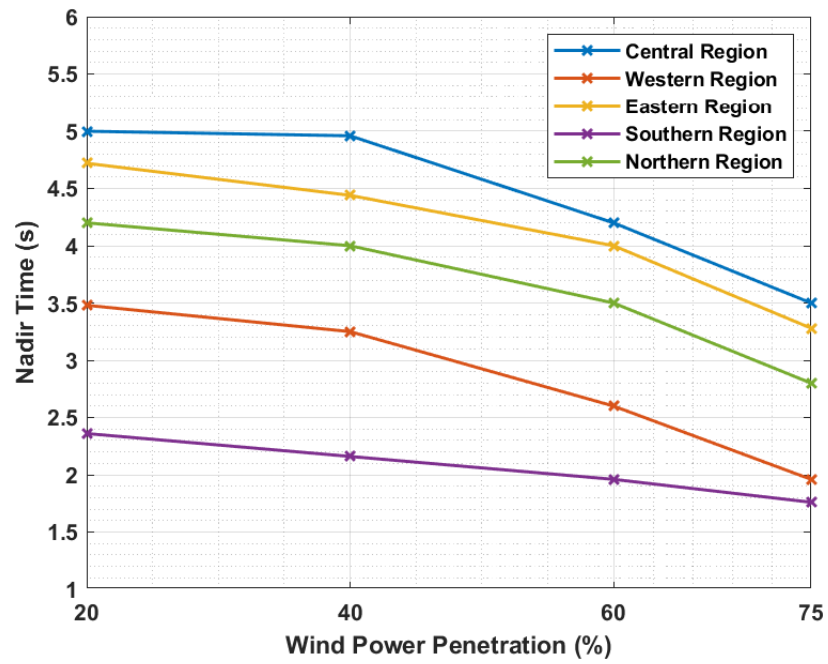
penetration of wind power increases, the settling time also increases. This increase is more significant after penetration of 60%, especially in the Western regions.



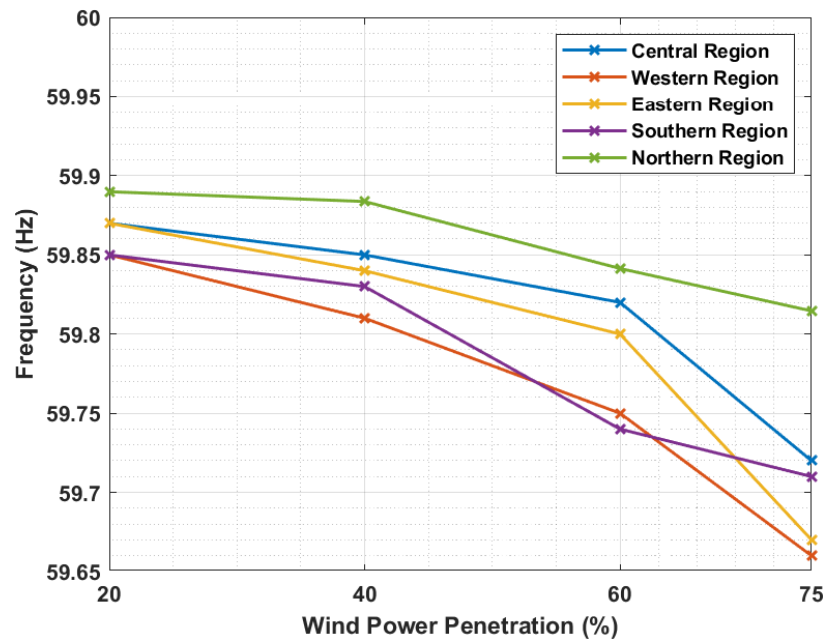
**Figure 5.17:** Variation in ROCOF with the increasing wind power penetration across five regions.



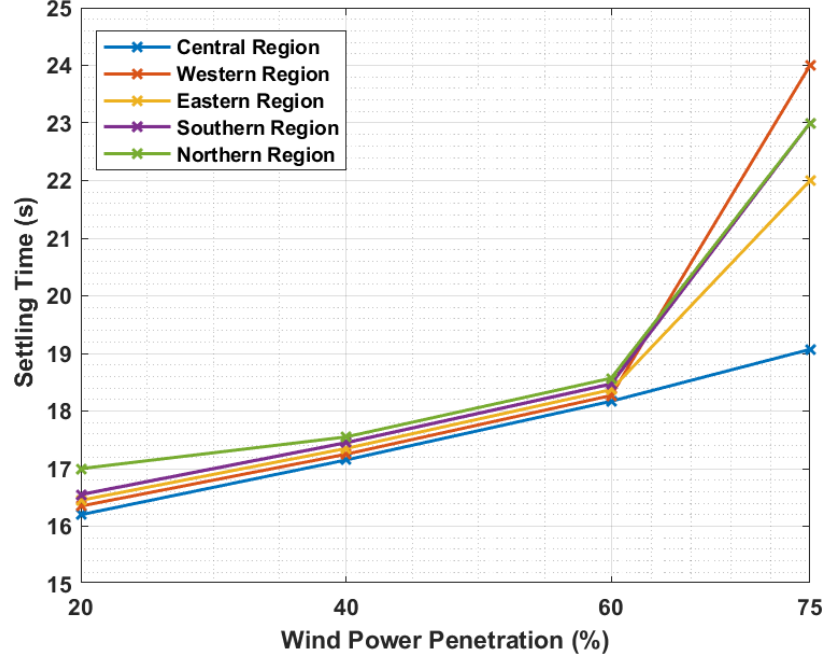
**Figure 5.18:** Variation in Frequency nadir change with the increasing wind power penetration across five regions.



**Figure 5.19:** Variation in Nadir time changes with the increasing wind power penetration across five regions.



**Figure 5.20:** Variation in Settling frequency change with the increasing wind power penetration across five regions.



**Figure 5.21:** Variation in Settling time with the increasing wind power penetration across five regions.

### 5.4.3 Impact Wind Turbine Penetration on Under-Frequency Load Shedding

Under-frequency load shedding (UFLS) is implemented to maintain the frequency of the power system within its nominal range after loss of generation. The main idea behind the UFLS is to disconnect a sufficient load to restore the frequency to its normal level and avoid total system breakdown (115). In this study, the UFLS limit is set at 59.5 Hz according to SAGC (29).

This section evaluates how high wind turbine penetration affects the UFLS system in the Saudi power grid. A standard emergency scenario is applied across the five operational areas of the Saudi power grid and the resulting frequency responses are documented. Table

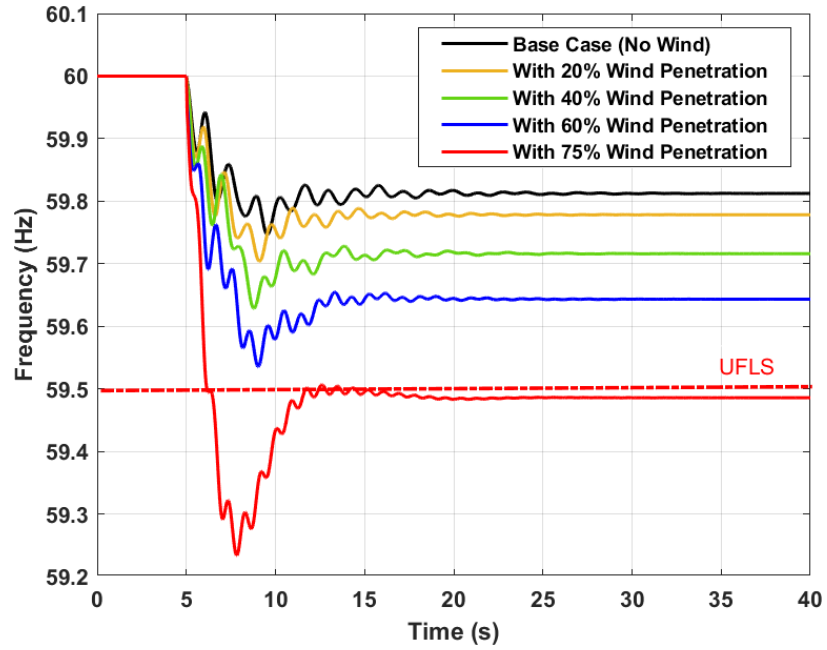
5.5 gives information on these contingencies. Each situation is simulated for 40 seconds and the frequency responses are shown in Figures 5.22 to 5.26 for each of the five regions.

The frequency nadir for the 60% penetration scenario of wind power in the central region was slightly above 59.5 Hz, as shown in Figure 5.22. In contrast, the nadirs for 75% penetration scenarios fell below this position. In the Western region, the results in Figure 5.24 show that UFLS can be activated in situations with penetration of 60% and 75% wind power when there is a loss of 1601 MW of generation. In contrast, in all wind turbine penetration scenarios inside the eastern region, the frequency nadirs remained much higher than UFLS, except in the case of 75%, as Figure 5.23 shows. This considerable margin is due to the higher generating capacity of the region compared to its load demand.

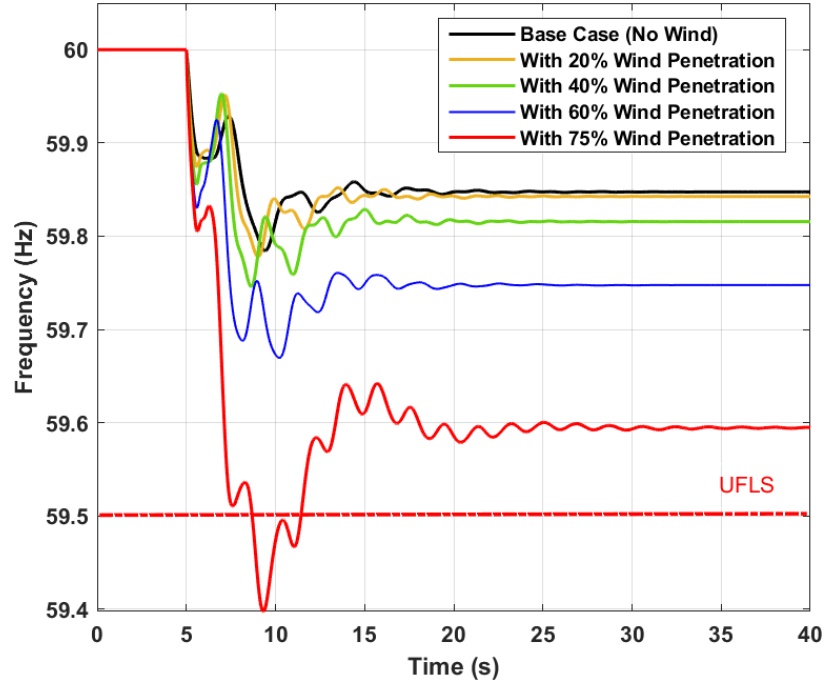
As illustrated in Figure 5.25, the frequency nadir did not reach the UFLS limit for wind turbine penetration 75%. However, the frequency nadir is close to the UFLS limit due to this disturbance in the northern region under such high penetration, which is due to the low load demand in the northern region. The frequency nadir in the southern area remained above 59.5 Hz for all scenarios of penetration of wind power, except when penetration reached 60% and 75%, as Figure 5.26 shows. This shows that the southern region grid is at risk of activating UFLS actions due to the high penetration level of wind power.

**Table 5.5:** Showing a summary of the generation plants data for trips in the simulation

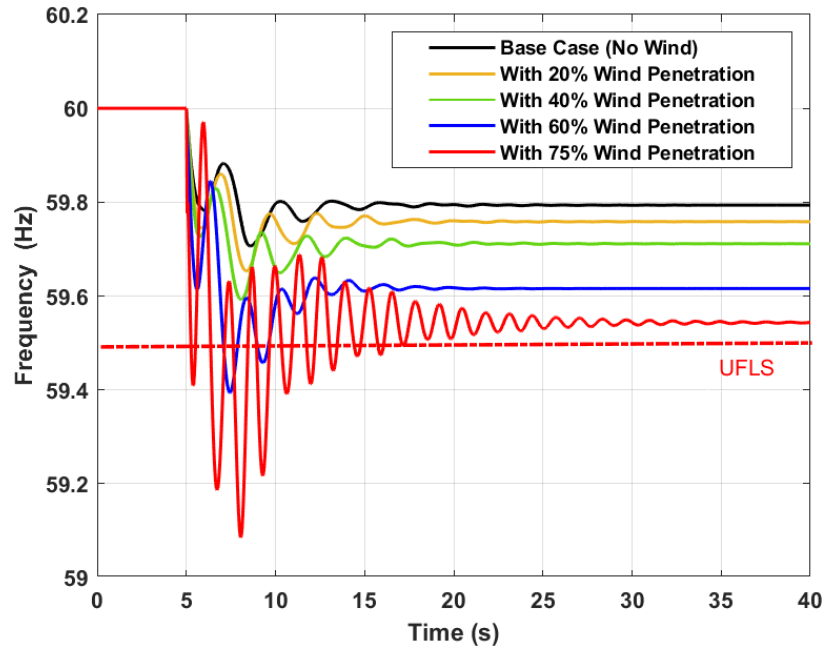
| Region | Generation Tripping Bus | Power Tripped (MW) | Frequency Response Bus |
|--------|-------------------------|--------------------|------------------------|
| COR    | RIYADH (Bus 330)        | 1,473              | RIYADH (Bus 301)       |
| EOR    | RAS KHAIR (Bus 234)     | 1,319              | JUBAIL (Bus 230)       |
| WOR    | SHAIBA (Bus 141)        | 1,601              | JEDDAH (Bus 145)       |
| NOR    | TABOUK - ALJOUF         | 1,175              | TURAIF (Bus 509)       |
| SOR    | ALBAHA - SHUQIQ         | 1,251              | ABHA (Bus 427)         |



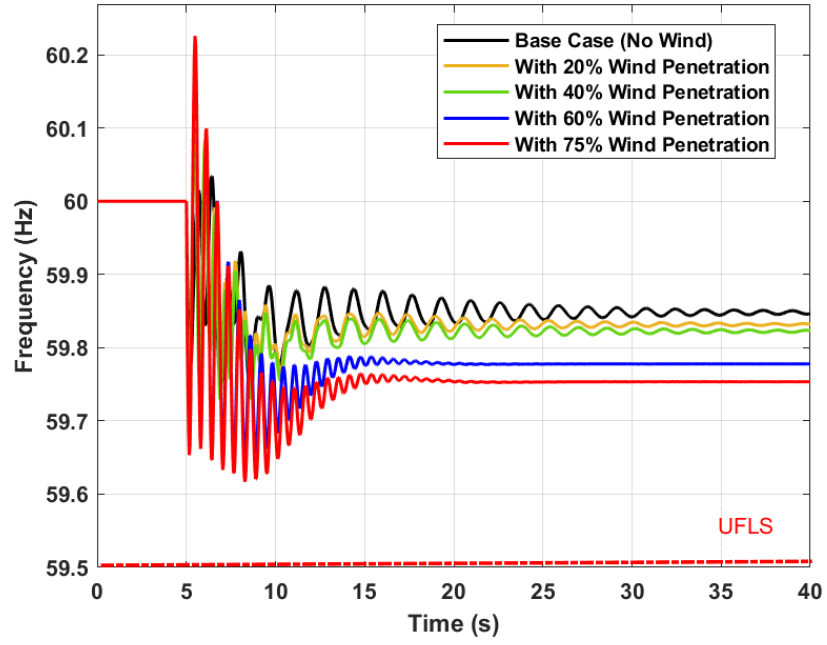
**Figure 5.22:** Frequency responses with different wind turbine levels penetration following a generator tripped 1473 MW in the COR region.



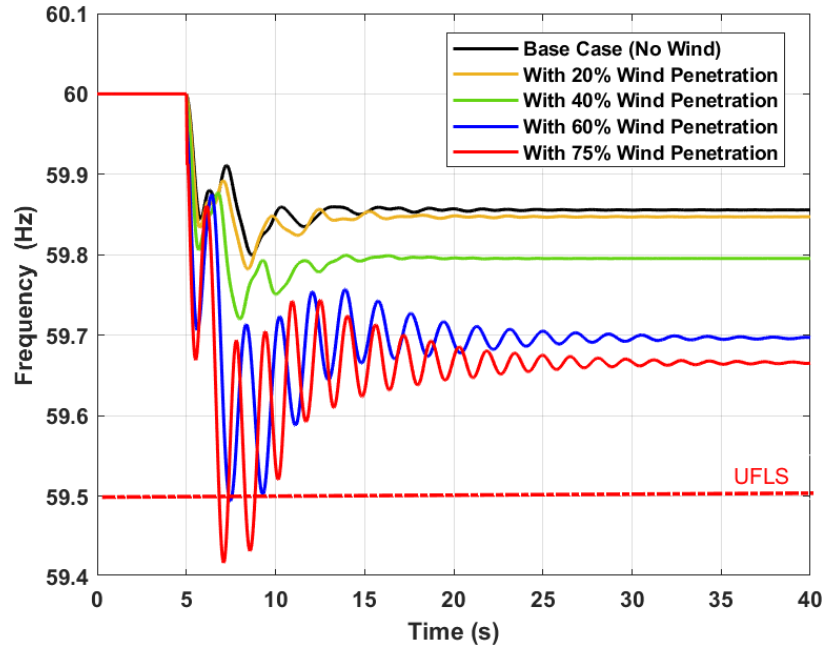
**Figure 5.23:** Frequency responses with different wind turbine levels penetration following a generator tripped 1319 MW in the EOR region.



**Figure 5.24:** Frequency responses with different wind turbine levels penetration following a generator tripped 1601 MW in the WOR region.



**Figure 5.25:** Frequency responses with different wind turbine levels penetration following a generator tripped 1175 MW in the NOR region.



**Figure 5.26:** Frequency responses with different wind turbine levels penetration following a generator tripped 1251 MW in the SOR region.

#### 5.4.4 Impact of Tripping a Large Wind power farms

Tripping a large wind turbine plant during periods of high penetration of wind power can have a significant impact on the power grid, primarily affecting its stability and operational efficiency. The high penetration of wind power means that the grid has less rotational inertia, since wind turbines typically do not contribute to inertia in the same way as conventional thermal power plants (26).

The reasons for tripping a wind plant can be varied, including both environmental and technical factors. High wind speeds can cause turbines to shut down to avoid mechanical damage, a safety feature known as the "cut-out speed" operation (116). Furthermore, disturbances in the grid, such as transmission line faults or substation equipment failures, can require the disconnection of a wind plant to protect the broader grid and the turbines themselves (14). In this part, a tripped large wind plant and two cases are investigated on the Saudi synthetic power grid.

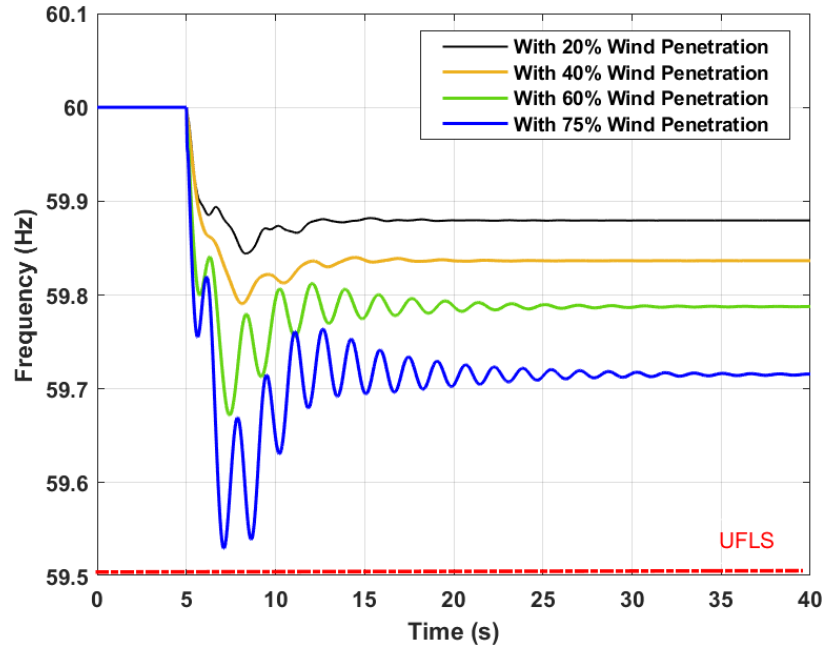
In the first case, when the wind power farms at bus 140 in the Western region have been tripped out. Wind power farms generated about 801 MW at the time of disconnect. Figure 5.27 shows the frequency response in bus 113 when wind penetration increased to under 20%, 40%, 60% and 75% penetration levels.



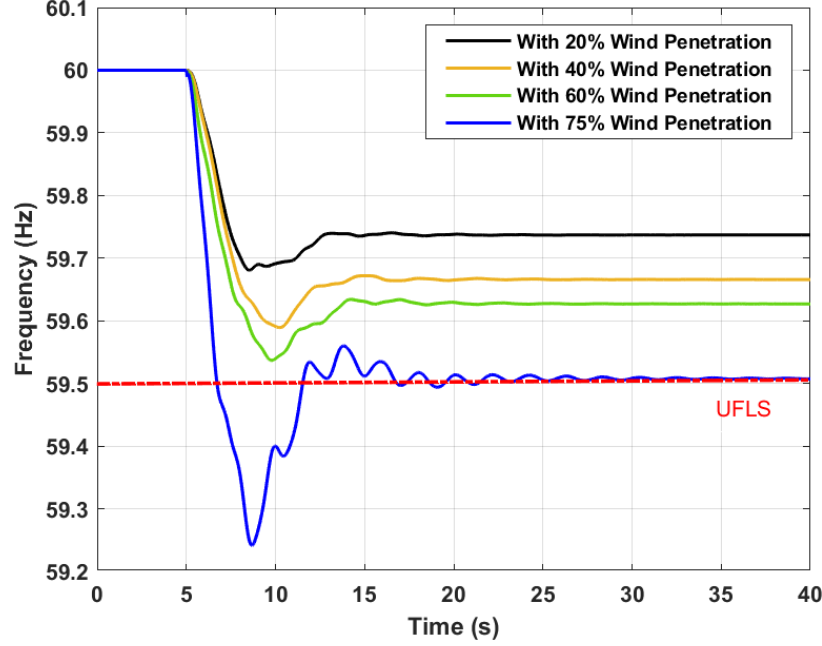
In the second case, when the wind power farms at bus 352 in the central region was tripped out, the wind power plants generated approximately 1964 MW at the time of disconnect. Figure 5.28 shows the frequency response on bus 302.

It is obvious that sudden disconnection of a significant wind plant can cause a significant imbalance in the power system when the power grid is provided by wind energy.

The increasing number of wind power farms seems to clearly affect the frequency response. The tripping plant caused oscillations in the system frequency, and its value was influenced by the penetration level, with higher wind power penetration leading to oscillation . In the western region, the frequency nadir did not reach the UFLS limit in the 75% case of penetration of wind turbines 75%, as illustrated in Figure 5.27, despite a notable decrease in frequency response.



**Figure 5.27:** Frequency responses with different wind turbine levels penetration after a wind power farm tripped 806 MW in the WOR region



**Figure 5.28:** Frequency responses with different wind turbine levels penetration after a wind power farm tripped 1964 MW in the COR region

#### 5.4.5 Impact of Installed Full Wind Penetration in One Region

Installing full wind penetration in one region of the Saudi power grid may have significant and different effects. A region can achieve full wind penetration when it produces enough wind energy to meet all of its electrical demand. This objective has the potential to change the dynamics of the regional power grid, improving sustainability but also technological difficulties. A primary consequence of complete wind penetration is improved environmental sustainability.

Regions such as the North have been identified as optimal locations for wind power due to their consistently high wind speeds. The wind profile in this area encourages large-scale wind farms, which will lead to substantial investments in wind energy projects. In addition to having strong winds, this region has the geographical benefit of being more unobstructed,

enabling wind energy production to be more effectively. Wind turbine plants have replaced all conventional machines in the North Region. Two cases are presented to demonstrate the frequency response.

In the first case, the wind power farms on bus 529 in the northern region was tripped out. At the time of disconnection, the wind power farm generated about 527 MW. Figure 5.29 shows the frequency response in NEOM bus 535 when the wind penetration increased below the penetration levels of 20%, 40%, 60%, and 75%.

It can be seen that tripping such wind power plants generated noticeable oscillations in frequency response, as Figure 5.29 is significantly reduced, there is still enough margin for the grid to avoid UFLS actions.

In the second scenario, this part simulates the worst-case scenario of losing a conventional power plant in different regions when all conventional machines in the northern region are replaced with wind turbine farms. In order to investigate the dynamic behavior of the grid at levels of penetration of wind power as low as 75%, the table shows the amount of power tripped in each region.

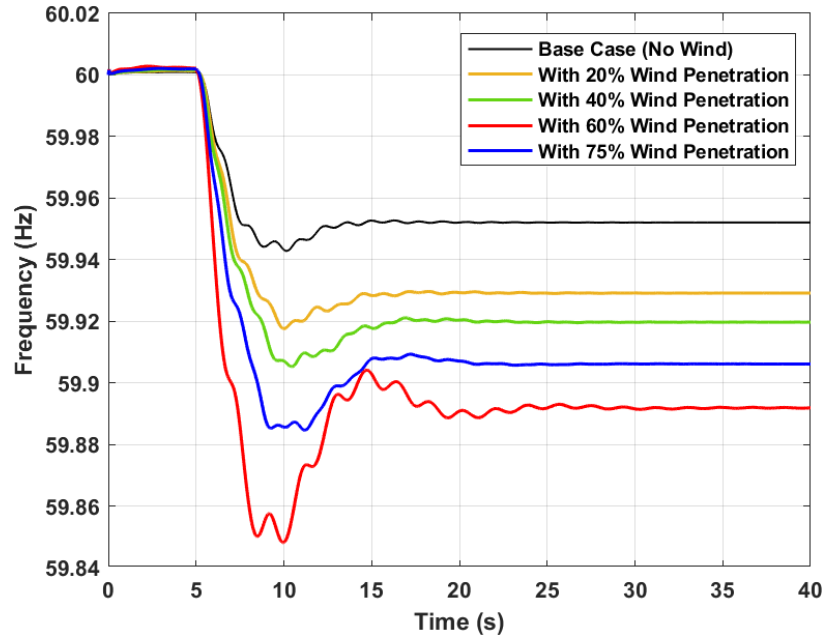
It can be seen that the frequency nadir associated with the wind power penetration scenario 75%, as shown in Figure 5.30, was marginally below 59.5 Hz when a 1474 MW in the central region tripped, causing the UFLS to activate and lose some load. The nadirs of the other penetration scenarios were higher than 59.5 Hz.

As a result, during the installation of full wind power in the Northern region, it can be seen that the Saudi synthetic system power could tripped of approximately 900 MW of power generation without losing its stability. These results demonstrate that electrifying

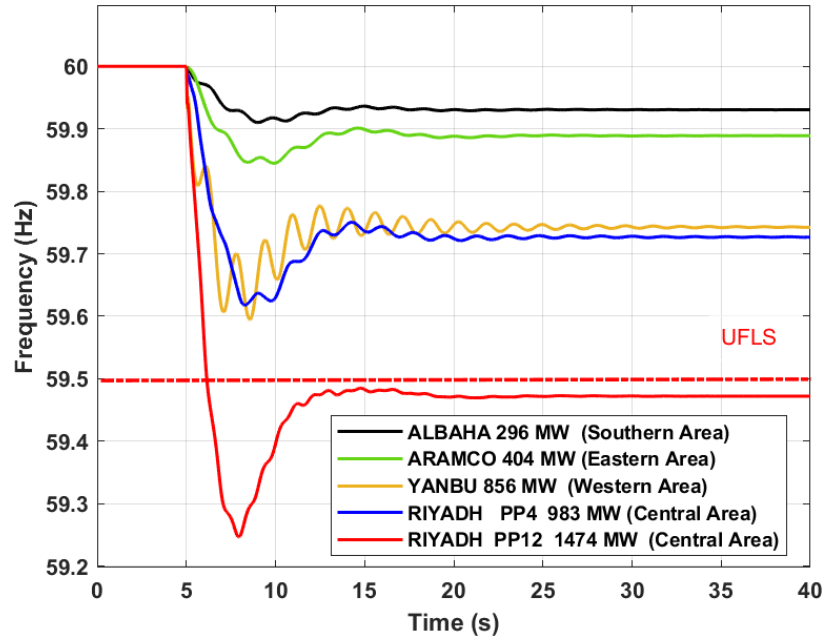
small areas in the Saudi power grid completely with wind power would not raise serious concerns with regard to frequency stability, considering the fact that it can receive enough power from other areas.

Maintaining stability in the electricity grid requires reducing the risk of outages across all wind power facilities as a result of adverse weather conditions. Significant power outages can result from weather-related disturbances (116). Developing strong protective measures that can mitigate the effect of such disruptions is essential to improving this. This process can include enhancing grid stability, varying the sources of energy used, and improving predictive weather models to make proactive adjustments to power outputs. However, the economic feasibility of these preventive measures could be challenging, as they require large investments in infrastructure and technology (7).

An alternative approach considering the proposed High Voltage Direct Current (HVDC) link between the Saudi and Egyptian grids is an alternate strategy to improve grid resilience against the interrupted nature of wind power generation. In times when wind output is insufficient, this connection can allow the exchange of up to 3,000 MW of electricity, decreasing the risk involved in depending only on one energy source and serving as an additional source of energy (117). In addition, by reducing consumption and helping reduce carbon projects, this setup improves more effective management of renewable energy resources, improves the use of available electricity, and could produce benefits for the economy and the environment (118).



**Figure 5.29:** Frequency responses at NEOM bus 535 with different wind turbine levels penetration after a wind power farm tripped 527 MW in the NOR region.



**Figure 5.30:** Frequency responses of nadir associated with the 75% wind power penetration scenario and amount of power tripped in each region.

## 5.5 Summary

In this chapter, the effect of high wind power penetration on frequency stability in the SSEG is evaluated. The frequency responses are evaluated at different levels of penetration of wind turbines (20%, 40%, 60%, and 75%) in different regions under different scenarios. Wind power farms in all operating regions are replaced by displacing existing conventional generators. The PSS/E group model reference generation type 4 WTG generic wind turbine dynamic model represents the dynamic performance of wind power farms. The effect of high wind power penetration in the SSEG on the system frequency response has been shown through the analysis of many case studies:

- A synthetic model simulation was created that simulates wind power penetration scenarios and their impact on the stability and security of the Saudi electricity grid.
- This synthetic model was tested with disturbances in different regions to evaluate the simulation results and compare them with SAGC standards.
- It was noted that the loss of more than 800 MW of generation during the 40% penetration of wind energy does not affect frequency stability in all regions.
- During the installation of full wind power in the Northern region, it was found that the synthetic Saudi system power can remain stable with a tripping of about 900 MW of power generation without losing its stability.
- During frequency metrics, it is verified that adding more wind power sources increases the ROCOF while reducing the nadir frequency and the settling frequency.

- The Western Region shows the most significant decrease in the frequency nadir as the penetration of wind power increases, while the Northern Region shows the least significant decrease. This is due to the increased residential and industrial loads in that region.
- According to the frequency response results in this chapter, measures should be used to mitigate and control frequency response degradation.

# Chapter 6

## MITIGATION MEASURES AND CONTROL STRATEGIES FOR FREQUENCY REGULATION

### 6.1 Overview

As shown in the previous chapter, the inertia of the power system is being reduced due to the increasing penetration of wind energy. This chapter aims to discuss potential mitigation measures and control strategies to enhance frequency regulation in SSEG. Integration of battery energy storage systems (BESS). In addition, the second approach involves the study to increase the number of generators equipped with active regulators in the stability of SSEG. The measures and proposed solutions provided here are intended to better evaluate and manage the effects of renewable integration on grid stability.



## 6.2 Improving the Frequency Response by Integrating Battery Energy Storage Systems

As shown in the previous chapter, the SSEG model, with high shares of wind turbine generators (WTGs), faced challenges due to reduced system inertia, where the total generation capacity with active turbine governors was only 22.28% of the total generation capacity of the system. Therefore, with low inertia, conventional units cannot provide sufficient frequency support. This happens because renewable energy displace conventional generators, which naturally help stabilize grid frequency through their rotating masses. With lower inertia, conventional units cannot provide enough frequency support (91). So, the grid becomes more vulnerable to sudden power imbalance. For instance, in the SSEG model, conventional generators that remained in 75% and 60% WTG penetration were unable to adequately compensate for frequency drops during disturbances. This caused the activation of Under-Frequency Load Shedding (UFLS). Additionally, the variable nature of wind power introduces additional instability, as uncertainty and fluctuations in the output of WTG can cause frequency deviations, making difficulties for the grid to maintain steady operation (119). Furthermore, interrupted power generation from WTG can increase frequency deviations and further reduce frequency stability (120).

There are multiple strategies that can be employed to address these challenges. High-voltage direct current (HVDC) systems present a more advanced alternative, using efficient long-distance power transmission to reduce losses and improve grid interconnect (121).

Saudi Arabia plans several HVDC projects to modernize its grid, including the EOR-COR interconnection links (500 kV), which are intended to connect wind and solar rich eastern regions with high-demand central hubs by 2029. Similarly, the NEOM-Yanbu HVDC line, (525 kV) project, is set to power the future NEOM industrial city with 100% clean energy, with its first phase operational by mid-2027. Internationally, the Saudi-Egypt HVDC interconnection will enable cross-border exchange beginning in the late 2028 (122; 123; 124).

In recent years, battery energy storage systems (BESS) have become an economically effective solution. Battery prices, for example, have declined more than 60% in the last three decades, due to the fact that the implementation of ESS has become economically feasible for frequency regulations (125). In Saudi Arabia, it can couple energy storage systems with HVDC to get the benefits of reducing the variability of wind power. In the future, if projects are implemented with the combined use of the HVDC expansion and ESS, they will work effectively together, with each supporting and enhancing the other.

One of the mitigating measures procedures, integration energy storage systems plays a critical role in compensating for the variability of wind energy (126). Integrating (BESS) into the Saudi Arabian power grid represents a cornerstone in the transition of the nation to sustainable energy systems. In addition, investing in battery technology for wind energy projects in Saudi Arabia is also a strategic economic move (127). Although the economic analysis of energy storage systems (ESS) is not addressed in this research, here it will only determine the optimal storage capacity for specific power system applications, which remains critical to ensuring efficient and sustainable operations.

In this study, the battery energy storage system (BESS) model in PSS/E is used which using a custom framework composed of three key modules, REPCA (generic plant control model), REECC (generic electrical control model) and REGCA (generator/converter model). These modules collectively simulate the dynamic characteristics of the BESS. In power flow, the ESS is represented as a single generator connected to a selected bus. The single model block structure of the BESS model is shown in (8). In the electrical control module (REECC). This module acts on active and reactive power references from the plant controller module, with feedback of terminal voltage for specification of a prescribed reactive control response during voltage dip and feedback of generator power output for monitoring the state of charge (SOC) of battery and setting appropriate active current limits. The REPCA module governs the overall control and coordination of the BESS, while the REECC module manages the electrical interactions with the grid, and the REGCA module simulates the physical behavior of the battery. The typical values of the parameters and more details about this model can be found in (3; 106).

In this study, batteries are installed at different places (SSEG), which is installed at eight locations within each region to ensure comprehensive coverage and optimal grid support. The capacity of the BESS is incrementally increased across five levels, which is 25 MW, 50 MW, 100 MW, 150 MW, 200 MW, to evaluate the impact of different storage capacities on frequency regulation. This incremental approach allows for a detailed evaluation of how different BESS sizes influence the grid ability to recover from disturbances, such as sudden generator tripping. For example, in the Central Region, eight BESS units are installed in

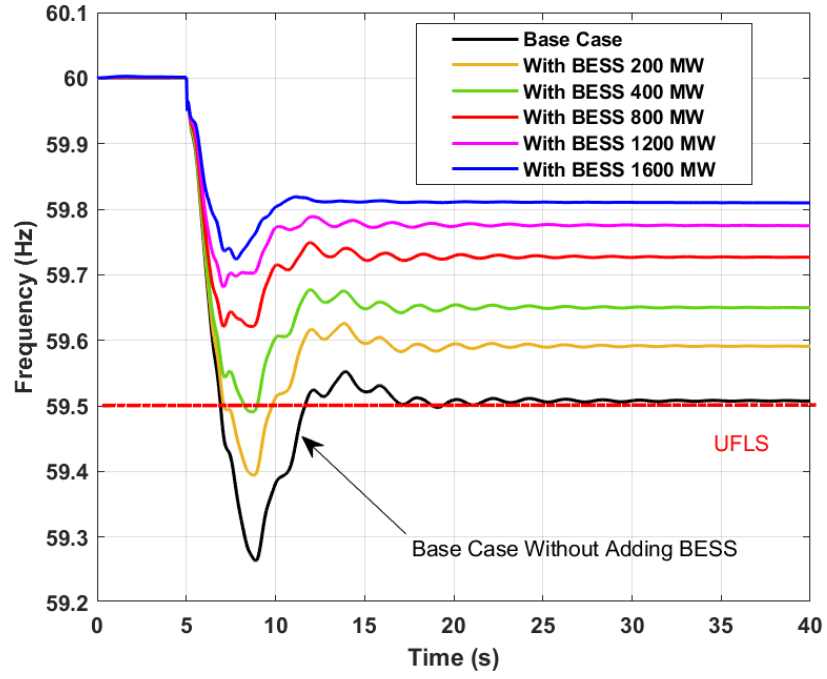
buses 315, 317, 321, 327, 330, 332, 300, and 335, with capacities ranging from 25 to 200 MW, as shown in Table 6.1.

**Table 6.1:** Placement and Size of BESS at the SSEG

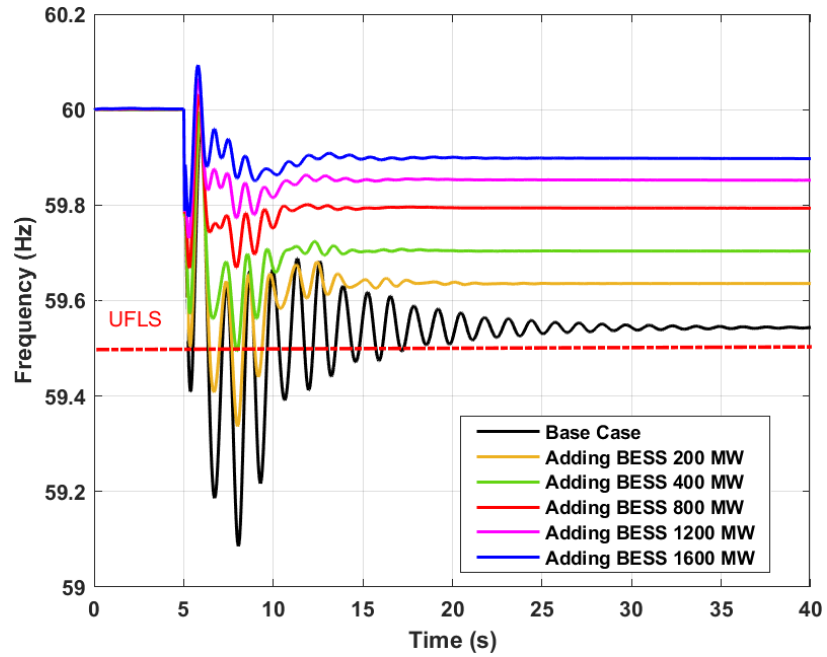
| <b>BESS Capacity Level</b> | <b>Region</b>   | <b>Buses</b>                           | <b>Capacity</b> |
|----------------------------|-----------------|----------------------------------------|-----------------|
| <b>Level 1 (25 MW)</b>     | Central Region  | 315, 317, 321, 327, 330, 332, 300, 335 | 200 MW          |
|                            | Eastern Region  | 204, 206, 207, 208, 209, 212, 216, 220 | 200 MW          |
|                            | Western Region  | 112, 113, 115, 116, 120, 137, 141, 143 | 200 MW          |
|                            | Southern Region | 407, 411, 413, 415, 417, 419, 421, 443 | 200 MW          |
| <b>Level 2 (50 MW)</b>     | Central Region  | 315, 317, 321, 327, 330, 332, 300, 335 | 400 MW          |
|                            | Eastern Region  | 204, 206, 207, 208, 209, 212, 216, 220 | 400 MW          |
|                            | Western Region  | 112, 113, 115, 116, 120, 137, 141, 143 | 400 MW          |
|                            | Southern Region | 407, 411, 413, 415, 417, 419, 421, 443 | 400 MW          |
| <b>Level 3 (100 MW)</b>    | Central Region  | 315, 317, 321, 327, 330, 332, 300, 335 | 800 MW          |
|                            | Eastern Region  | 204, 206, 207, 208, 209, 212, 216, 220 | 800 MW          |
|                            | Western Region  | 112, 113, 115, 116, 120, 137, 141, 143 | 800 MW          |
|                            | Southern Region | 407, 411, 413, 415, 417, 419, 421, 443 | 800 MW          |
| <b>Level 4 (150 MW)</b>    | Central Region  | 315, 317, 321, 327, 330, 332, 300, 335 | 1200 MW         |
|                            | Eastern Region  | 204, 206, 207, 208, 209, 212, 216, 220 | 1200 MW         |
|                            | Western Region  | 112, 113, 115, 116, 120, 137, 141, 143 | 1200 MW         |
|                            | Southern Region | 407, 411, 413, 415, 417, 419, 421, 443 | 1200 MW         |
| <b>Level 5 (200 MW)</b>    | Central Region  | 315, 317, 321, 327, 330, 332, 300, 335 | 1600 MW         |
|                            | Eastern Region  | 204, 206, 207, 208, 209, 212, 216, 220 | 1600 MW         |
|                            | Western Region  | 112, 113, 115, 116, 120, 137, 141, 143 | 1600 MW         |
|                            | Southern Region | 407, 411, 413, 415, 417, 419, 421, 443 | 1600 MW         |

In order to evaluate the effectiveness of mitigation measures, a set of loss generator events with different capacities was implemented across different regions. Initially, the events applied in the (SSEG) without an (ESS), then followed by integrating ESS into the grid with different levels of energy storage capacity under 75% WT penetration. Eight units (BESS) were installed on eight buses in each region with different power ratings.

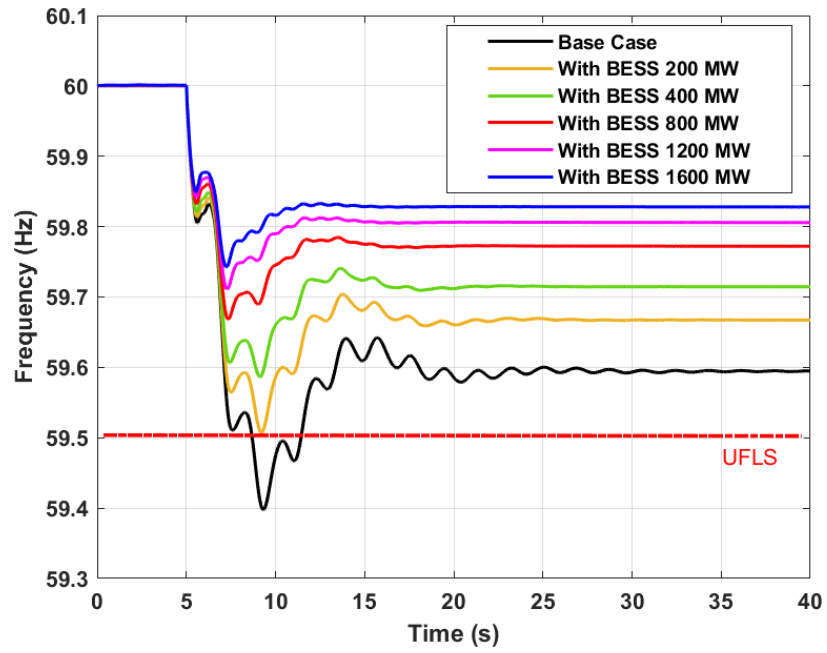
The frequency response is observed as shown in the figures from 6.1 to 6.4. It can be seen that BESS significantly reduces frequency drop. Compared to the base case scenario. For example, the frequency drop with 1600 MW BESS is reduced by 0.47 Hz in the central region. Although the frequency metrics of all proposed BESS capacities show significant improvements compared to the scenarios without BESS, the 200 MW and 400 MW BESSs are unable to prevent the frequency drop from falling below the UFLS position in a range of regions. Therefore, regarding power ratings, the BESS should be sized at least 33% of the highest emergency load in the area to prevent UFLS activation. Furthermore, installing a larger capacity than this to manage the base frequency during such events may not be economical.



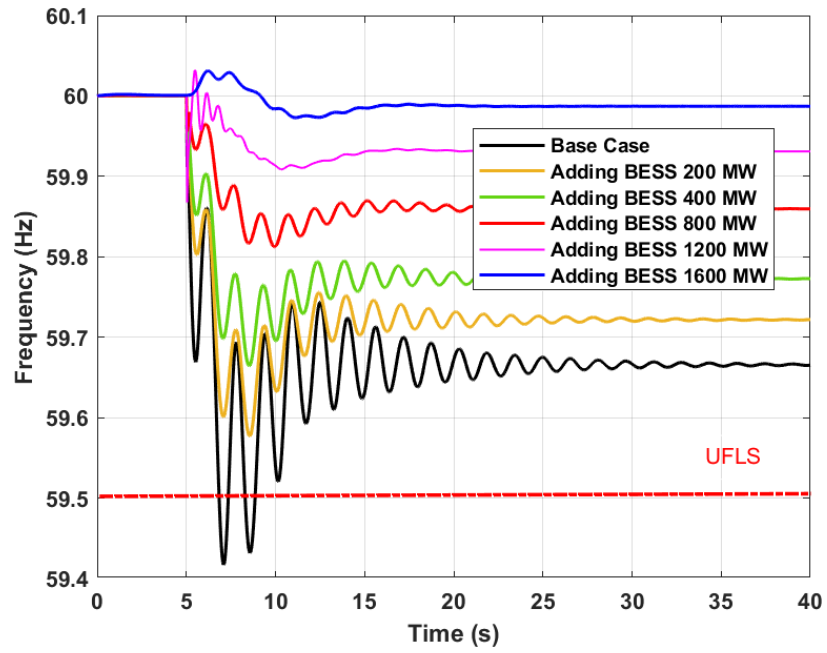
**Figure 6.1:** Frequency responses when increasing BESS capacitance in the Central Region.



**Figure 6.2:** Frequency responses when increasing BESS capacitance in the Western Region.



**Figure 6.3:** Frequency responses when increasing BESS capacitance in the Eastern Region.

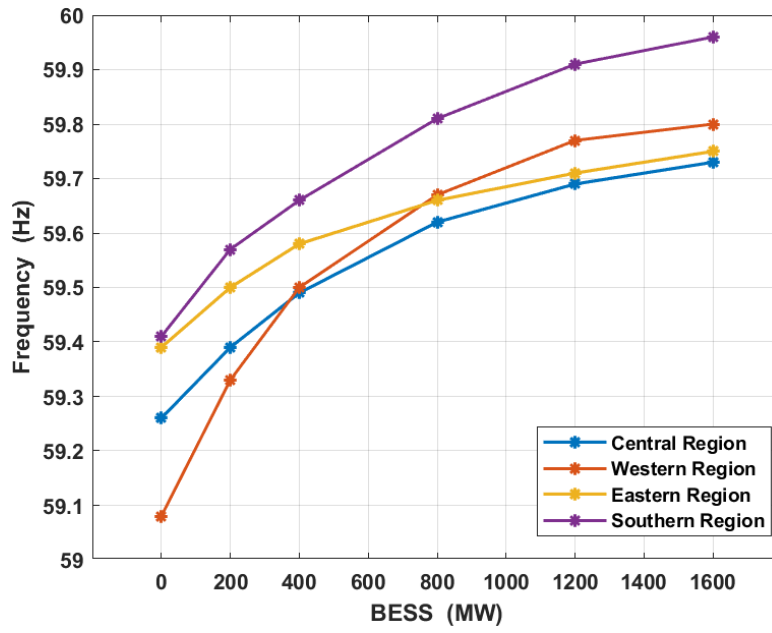


**Figure 6.4:** Frequency responses when increasing BESS capacitance in the Southern Region.

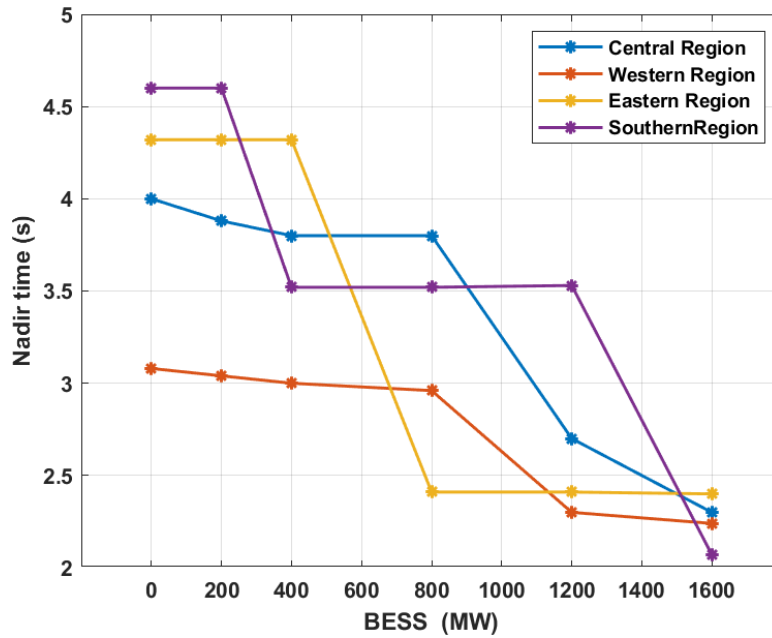
The graphs provided in Figures 6.5, 6.6, and 6.7, respectively, illustrate the impact of (BESS) on the frequency metrics of the system across different regions. Figure 6.5 shows the frequency nadir, which is the lowest frequency reached following a disturbance. As the BESS capacity increases from 0 to 1600 MW, the frequency nadir improves. The Central Region shows the lowest nadir but improves significantly with increasing BESS capacity, while the Southern Region starts higher and maintains better stability overall. This shows that higher BESS capacities can effectively mitigate frequency drops in the grid.

Figure 6.6 shows the nadir time. The graph shows that with the addition of BESS, the nadir time is shorter. The Central Region has the biggest decrease, it can be more stable with more BESS capacity. Figure 6.7 illustrates the settling frequency, the frequency level that the system stabilizes after a disturbance. Similarly to the frequency nadir, the settling frequency improves with higher BESS capacities, indicating a more stable system post-disturbance. The Southern Region consistently shows higher settling frequencies, suggesting better overall frequency stability. This is due to the low loads in that area, according to statistics. These findings emphasize the importance of integrating BESS into high-renewable energy grids to enhance frequency stability.

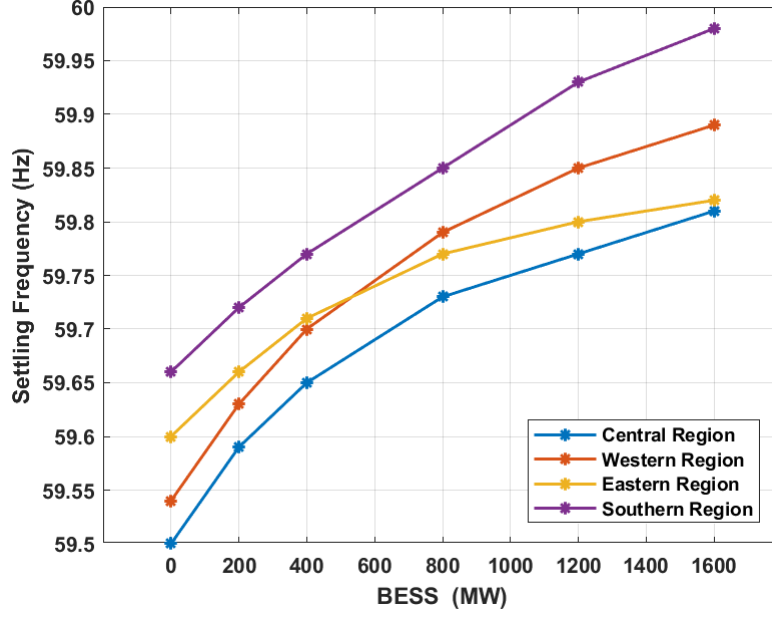




**Figure 6.5:** Frequency nadir response with different BESS capacities at different regions.



**Figure 6.6:** Nadir time response with different BESS capacities at different regions.

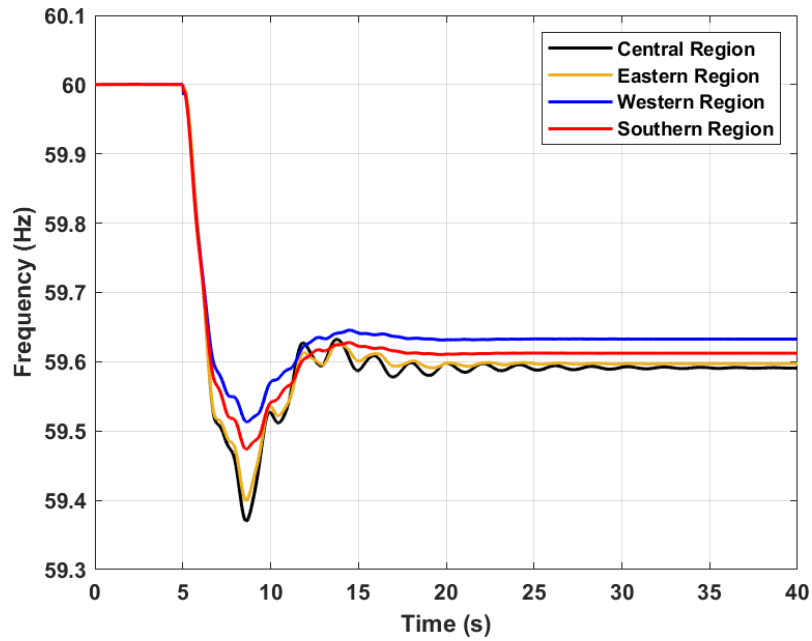


**Figure 6.7:** Settling frequency response with different BESS capacities at different regions.

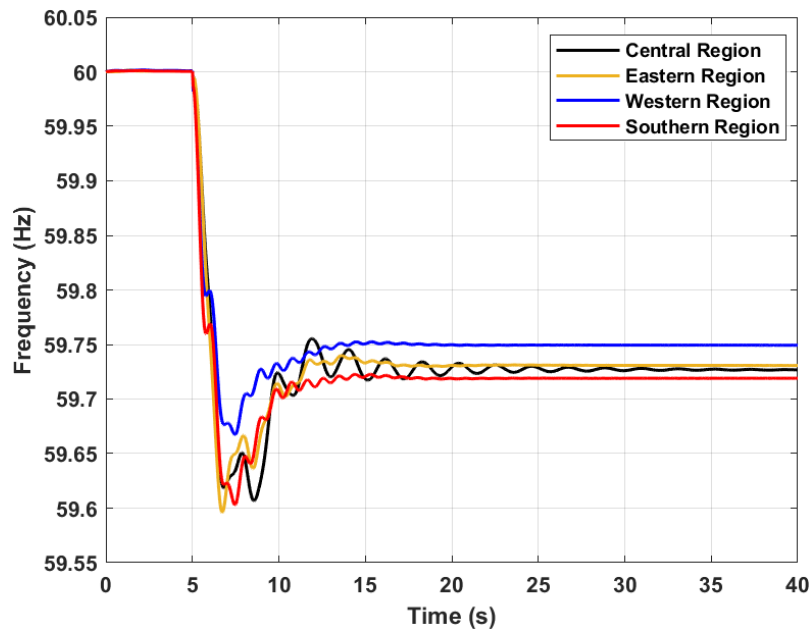
To evaluate whether the placement of BESS units affects the frequency response, the same event scenario was applied, which is just a tripped generator in the central region while installing eight BESS units in different regions. For example, frequency responses for two scenarios involving 200 MW and 800 MW of installed BESS are shown in two Figures 6.8 and 6.9 .

The figures show that the frequency response is different depending on where the BESS units are installed within the grid. This is because the sources distance between the BESS and the disturbance location affects how readily and effectively the BESS can respond to frequency deviations. The Central Region, which typically experiences higher load and larger generation losses, shows more significant frequency improvements when BESS units are installed near it. In contrast, the Southern Region, which has a more stable grid structure, exhibits smaller variations in frequency response no matter where BESS is located. Thus,

it becomes obvious that the location of BESS can influence the frequency response in the SSEG.



**Figure 6.8:** Frequency Responses During 200 MW BESS Capacitance at Different Region.



**Figure 6.9:** Frequency responses during 800 MW BESS capacitance at different region.

## 6.3 Improving the Frequency Response by Integrating Number of Generators with Active Governors

### 6.3.1 Increasing the Number of Generators with Active Governors

The integration of wind energy into power systems will impact inertia, as replacement of conventional synchronous generators will affect the power system. As discussed in Chapter 5, in scenarios with high wind power penetration of up to 75% . This leads to a decrease in frequency response, which can trigger the load shedding position (UFLS) due to low frequency, as shown in previous sections for scenarios with high wind penetration. To address this issue, two mitigation strategies frequency control practices are applied in this study which are increasing governor involvement and adjusting governor droop settings.

The second approach involves increasing the number of generators equipped with active governors. In the (SSEG) model, the total generation capacity is about 64,680 MW, with 14,402 MW (22.28%) generated by machines connected to active governors. However, as wind energy penetration increases, conventional machines are being replaced, and some of these replaced units have governor response capabilities.

The governor ratio ( $K_t$ ) is defined as the ratio between the governor-equipped generation capacity and the total system capacity (91). A lower  $K_t$  value indicates that fewer conventional synchronous generators can respond to grid disturbances. As wind penetration increases,  $K_t$  decreases significantly. For instance, in the original SSGE model, the base case has  $K_t = 22.28\%$ , but this drops to 10% at 75% wind penetration, as the generation capacity

with active governors is reduced to 6100 MW. To mitigate this, Kt is increased for many levels.

$$K_t = \frac{\text{Governor-Equipped Generation Capacity}}{\text{Total System Capacity}} \times 100$$

Most of the machines in the Saudi power grid are gas turbine units, steam turbine units, and combined cycle units, which can effectively respond governors to under-frequency events. Therefore, increasing the number of machines with active governors can restore the governor ratio to a more stable level. To mitigate this, Kt is increased as Table 6.2 shows the suggested scenarios.

**Table 6.2:** Governor Responsive Generation Capacity

| Case   | Governor Involvement (Kt) | Governor Capacity (MW) |
|--------|---------------------------|------------------------|
| Case 1 | 10%                       | 6,100                  |
| Case 2 | 17%                       | 11,400                 |
| Case 3 | 21%                       | 14,035                 |
| Case 4 | 31%                       | 19,955                 |

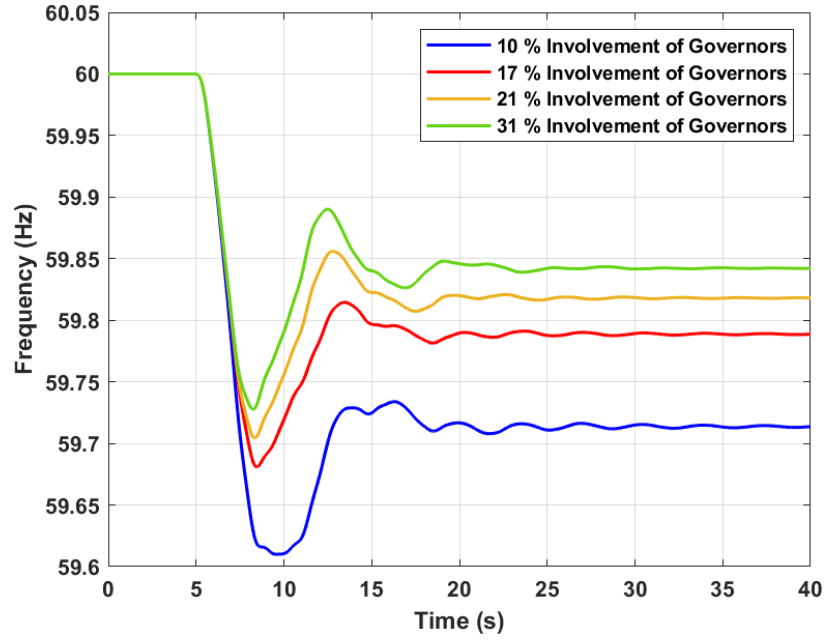
To investigate the impact of changing the governor ratio, a power plant generation was tripped on bus 352 in the COR, generating 1,946 MW. Figures 6.10 and 6.11 show the frequency responses for different governor ratios (10%, 17%, 21% and 31%) at 40% and 75% wind penetration levels, respectively, with different levels of governor involvement (Kt).

At 40% wind penetration, it was observed that deviations improve due to increased governor participation. For example, increasing Kt from 10% to 31% raises the frequency nadir from 59.6159 to 59.7287 Hz, demonstrating the applicability of this strategy across different penetration levels. Compared to the base case SSEG model with 75% wind energy when Kt is about 10%, it can be seen that increasing Kt to 31% improved the settling frequency by slightly more than 0.30 Hz, as shown in Figure 6.11.

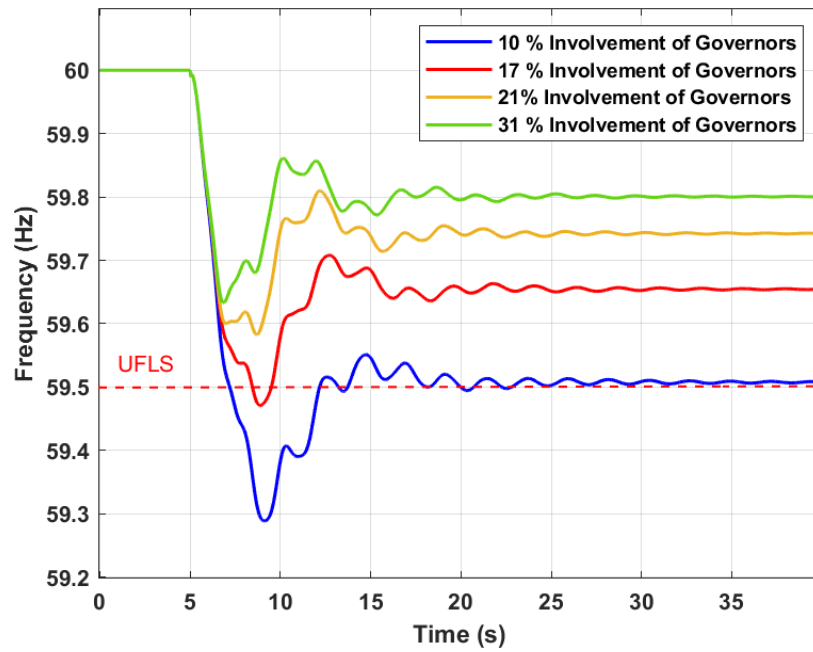
Therefore, Tables 6.3 summarize the frequency response metrics for all the suggested techniques, while Figure 6.12 provide visual comparisons of their performance.

**Table 6.3:** Impact of adjusting governor involvement on the frequency response metrics.

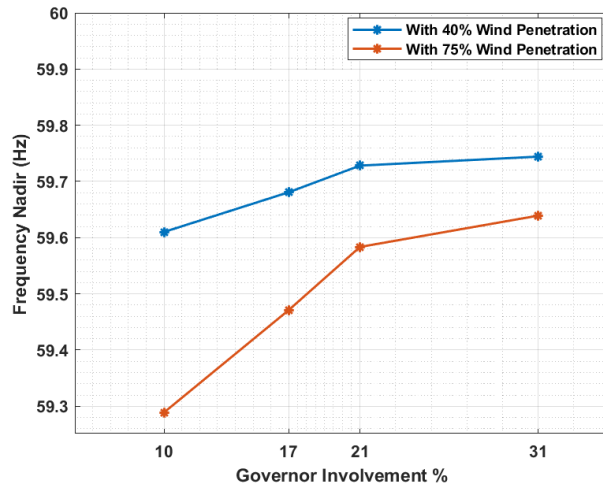
|                 | <b>Governor Involvement</b> | <b>Frequency Nadir (Hz)</b> | <b>Settling Frequency (Hz)</b> | <b>Nadir Time (s)</b> | <b>ROCOF (mHz/s)</b> |
|-----------------|-----------------------------|-----------------------------|--------------------------------|-----------------------|----------------------|
| <b>40% Wind</b> | 10%                         | 59.6159                     | 59.7166                        | 4.0201                | 0.095                |
|                 | 17%                         | 59.6808                     | 59.7902                        | 3.4412                | 0.092                |
|                 | 21%                         | 59.7042                     | 59.8181                        | 3.3601                | 0.088                |
|                 | 31%                         | 59.7287                     | 59.8424                        | 3.1601                | 0.085                |
| <b>75% Wind</b> | 10%                         | 59.2889                     | 59.5096                        | 4.1607                | 0.171                |
|                 | 17%                         | 59.4711                     | 59.655                         | 3.9208                | 0.134                |
|                 | 21%                         | 59.5835                     | 59.7431                        | 3.6401                | 0.114                |
|                 | 31%                         | 59.6392                     | 59.8007                        | 2.8801                | 0.093                |



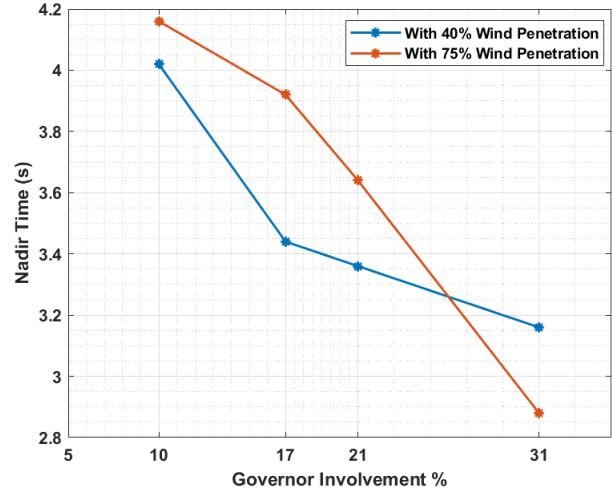
**Figure 6.10:** Frequency response with different levels of involvement of governors during 40% wind energy penetration



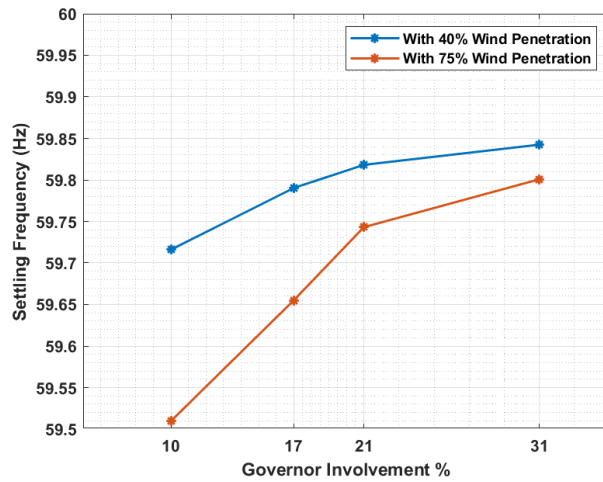
**Figure 6.11:** Frequency response with different levels of involvement of governors during 75% wind energy penetration



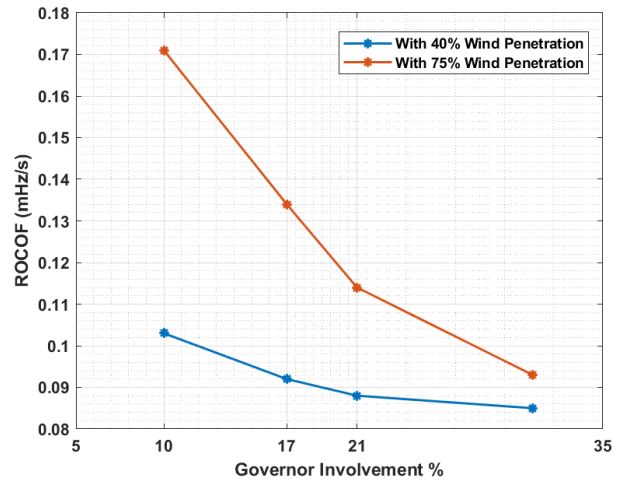
(a) Figure 1: Frequency Nadir



(b) Figure 2: Nadir Time



(c) Figure 3: Settling Frequency



(d) Figure 4: ROCOF

**Figure 6.12:** Visual comparison of frequency response metrics at 40% and 75% wind energy penetration levels.



### 6.3.2 Adjusting Governor Droop

Another mitigation measure to improve frequency response is to adjust the governor droop of the remaining synchronous machines. The governor function regulates how rapidly the governor responds to a disturbance in the system (91). A lower droop improves the frequency response, meaning it allows the system to react more response to disturbances. In conventional power plants, the droop setting is often around 5%, but reducing it to 3% enhances the speed of governor responding. However, for safe and reliable integration of renewable energy sources into the power grid, it is recommended to maintain a droop range between 3% and 5% (128). The governor droop control rate ( $R$ ) is represented by:

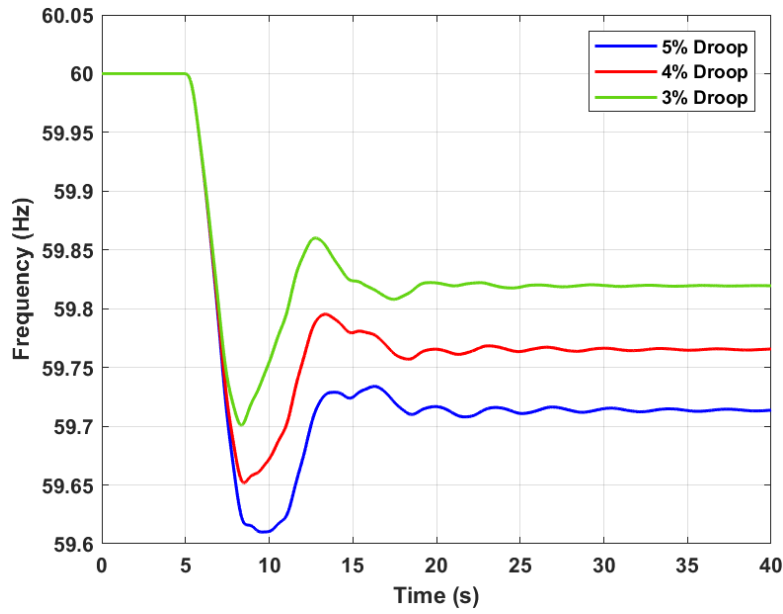
$$R = -\frac{\Delta f}{\Delta P}$$

Where  $\Delta f$  and  $\Delta P$  are the deviations in system frequency and power, respectively.

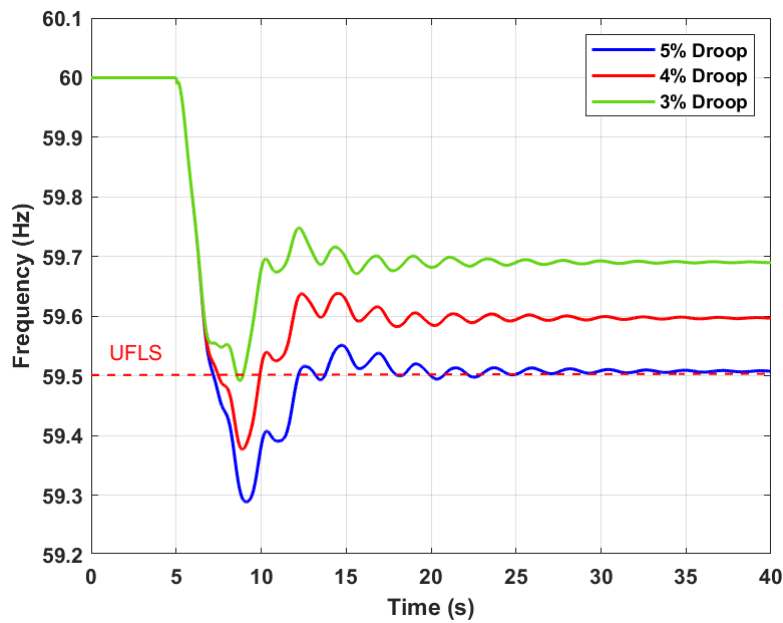
The simulation results with three governor droop settings are shown in Figure 6.13 and Figure 6.14 for 40% and 75% penetration instances, respectively,

It can be seen the impact of governor droop. At 40% wind penetration, reducing the droop from 5% to 3% improves the frequency nadir by 0.08 Hz (59.6159 to 59.7004 Hz) and the settling frequency by 0.11 Hz (59.716 Hz to 59.829 Hz). In the scenario of 75% wind penetration, the 3% droop design increases the frequency nadir by 0.20 Hz (from 59.2889 Hz to 59.4976 Hz) and the settling frequency by 0.18 Hz (from 59.5096 Hz to 59.6906 Hz). These improvements come from the stronger governor response enabled by lower droop values.

Therefore, the results validate the recommendation for a 3–5% droop range, confirming that optimized droop settings enhance grid stability.



**Figure 6.13:** Frequency response with different governor drops during 40% wind energy penetration



**Figure 6.14:** Frequency response with different governor drops during 75% wind energy penetration

### 6.3.3 Combined Effect of Governor Ratio and Droop

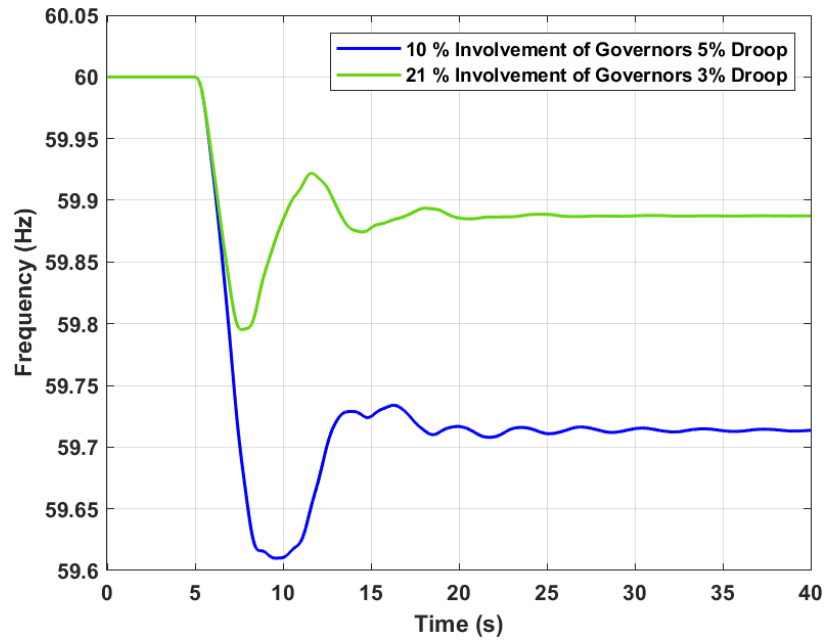
This scenario involves applying a combination of the two techniques, which shows significant improvement in frequency response. For example, increasing the governor ratio and reducing the governor droop show the frequency response for 40% and 75% wind penetration levels, respectively, with different governor ratios and droop settings.

Figures 6.15 and 6.16 illustrate the combined impact of increasing the involvement of the governor (Kt) and reducing the droop of the governor on the frequency response in the penetration of the wind 40% and 75%, respectively. For penetration of 40%, combining 21% Kt with 3% droop improves the frequency nadir to 59.7954 Hz and the settling frequency to 59.8872 Hz, compared to the base case (10% Kt, 5% droop) with a nadir of 59.6101 Hz and settling frequency of 59.716 Hz as shown in Table 5.5. The ROCOF decreases from 0.081 Hz/s to 0.074 Hz/s, indicating slower frequency decline. At 75% penetration, the same strategy (21% Kt , 3% droop) improves the frequency nadir by 0.34 Hz and ROCOF reduces to 0.131 Hz/s.

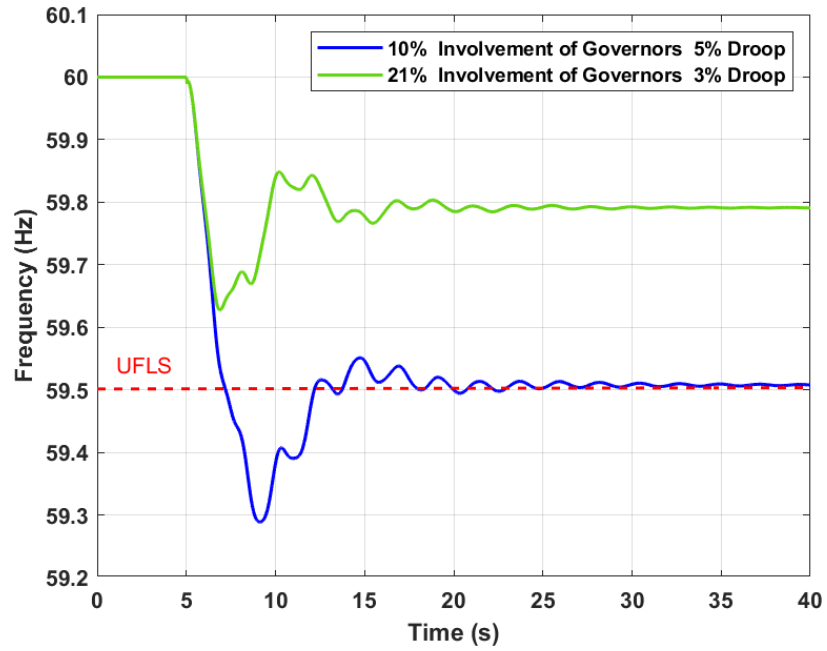
Therefore, Tables 6.4 summarize the frequency response metrics for all the techniques.

**Table 6.4:** Summarize the frequency response metrics for all the technique

|                                                 | 40% Wind          |                   | 75% Wind          |                   |
|-------------------------------------------------|-------------------|-------------------|-------------------|-------------------|
| Governor Involvement %<br>&<br>Governor Droop % | 10%<br>(5% Droop) | 21%<br>(3% Droop) | 10%<br>(5% Droop) | 21%<br>(3% Droop) |
| Frequency Nadir (Hz)                            | 59.6159           | 59.7954           | 59.2889           | 59.6276           |
| Settling Frequency (Hz)                         | 59.7166           | 59.8872           | 59.5096           | 59.7906           |
| Nadir Time (s)                                  | 4.0201            | 2.76014           | 4.16007           | 2.8401            |
| ROCOF (mHz/s)                                   | 0.095             | 0.074             | 0.171             | 0.131             |



**Figure 6.15:** Frequency response with different levels of involvement of governors and governors droop during 40% wind energy penetration



**Figure 6.16:** Frequency response with different levels of involvement of governors and governors droop during 75% wind energy penetration

These results demonstrate that coordinating higher governor participation with optimized droop settings enhances frequency stability by governor adjustments, particularly critical in high-renewable grids. This study validates that increasing the governor participation to 21% (Kt) and reducing the droop to 3% significantly enhance frequency stability in high-wind grids. At 75% wind penetration, these strategies improve the frequency nadir by 0.35 Hz and reduce the nadir time. Thus, to mitigate the increasing impact of frequency decrease during the wind power penetration case, maintaining the governor participation above the necessary position is critical. Moreover, the governor droop settings can also be modified to enhance frequency regulation.

## 6.4 Summary

This chapter evaluates mitigation strategies to enhance frequency stability in (SSEG) with high wind power penetration. Integrating battery energy storage systems (BESS) reduces frequency deviations and prevents under-frequency load shedding (UFLS). Optimal placement of BESS also improves response efficiency. Additionally, increasing the number of generators with active governors also improves frequency deviations. These strategies achieve the best results, contributing to grid stability even under maximum integration of renewable energy. The following key points summarize the results:

- Integration of 1600 MW of BESS will reduce frequency drops by 0.47 Hz and prevent UFLS activation. Moreover, smaller capacities (200 - 400 MW) may still activate UFLS in high-demand regions.
- Placing BESS near disturbance locations, such as the central region, improves response recovery and effectiveness rapidly.
- During governor participation, increasing  $K_t$  from 10% to 31% improves the frequency nadir by 0.35 Hz and reduces ROCOF at 75%.
- During droop adjustment, lowering the droop from 5% to 3% improves the governor response, improving the settling frequency by 0.28 Hz.
- Combining the governor participation ratio,  $K_t$ , from 10% to 21% strategies and reducing the governor droop from 5% to 3% yields the best results, stabilizing the grids even under 75% renewable integration.

# Chapter 7

## CONCLUSION AND FUTURE WORK

### 7.1 Conclusion

This study highlighted the impact of the integration of wind power on the stability of the Saudi electricity grid. As Saudi Arabia moves toward renewable energy, this shift represented a critical step in its energy strategy. This work created models for future research related to the integration of wind farms into the Saudi grid. It also provided a background for researchers to explore improvements, challenges, and evaluate and plan solutions.

The first part of this research focused on the construction of synthetic power system grids for the Saudi electric grid that are simulated geographically and statistically. The model was designed to have similar detailed characteristics according to the geographical constraints of real Saudi power systems, including compliance with Saudi code requirements and statistical

properties simulated in actual power grids. This synthetic model, consisting of 224 buses, represents accurate geographic coordinates, confirms that the system is dynamically stable, and validates the emphasis that the system under investigation exhibits dynamic stability based on code requirements.

The second part examined the critical aspects of integrating wind farms into the Saudi grid, focusing on compliance with the requirements of the grid code. Through detailed simulations, the study evaluated the fault ability and the reactive power capacity of wind farms to ensure system security and reliability. A detailed model of future wind energy resources in Saudi Arabia has been simulated and the performance of wind farms during grid faults such as voltage dips and internal grid interactions was evaluated. Additionally, the chapter compared technical strategies employed by various countries to achieve compliance with (LVRT). The results show that the evaluated wind farm met most grid code requirements, including effective fault handling under specific conditions. However, integrating solar photovoltaic (PV) systems, referred to as voltage drops near the point of connection (POC) below the grid code levels, proposed the need for grid code enhancements to address these challenges. Thus, these insights can help researchers in Saudi Arabia develop its approach, ensuring that wind and solar projects operate securely within the existing system.

The impact of high wind penetration levels on grid stability is a critical issue highlighted in the SSEGs. As wind penetration increases, the frequency response of the Saudi grid experiences significant changes following major events. It was observed that losing of more than 800 MW of generation during 40% wind penetration did not affect the frequency



stability in any of the regions. However, at certain levels of wind penetration, under frequency load shedding is activated, particularly in cases where wind penetration reaches 60% in most regions.

Regions like the Western Region experience a drop in frequency during outages at around 60% wind penetration, while the Northern Region shows greater flexibility. The collapse in frequency stability primarily referred to the low inertia system. Consequently, maintaining an adequate frequency response following major disturbances with high wind penetration causes a significant challenge.

However, it was also observed that higher penetration levels, such as 75%, also lead to higher rates of frequency change (ROCOF) and a lower frequency nadir, which can challenge the stability of the grid.

Finally, to address these challenges, the dissertation also evaluated several mitigation strategies to enhance grid stability. The integration of battery energy storage systems (BESS) is confirmed to be an effective solution to stabilize the frequency by reducing frequency deviations and preventing under frequency load shedding (UFLS). The placement of BESS near disturbance sources improves frequency response and effectiveness due to reduced frequency drops. The study demonstrated that the deployment of a 1600 MW BESS could reduce frequency drops by 0.47 Hz and prevent UFLS activation, particularly in high-demand regions. Moreover, using generators with active governors, such as governor droop and participation ratios, further enhanced the ability of the system to maintain frequency stability. These strategies, when combined, ensure that the grid can remain stable even

with maximum integration of renewable energy, providing a clear pathway to the successful implementation of Saudi Arabia's renewable energy goals.

## 7.2 Future Work

- Further studies are recommended that discuss the dynamic implications of integrating HVDC technology into the Saudi electricity grid for effects on grid stability and performance.
- Additional research is needed to evaluate the economic feasibility of penetration large-scale wind energy penetration. This includes evaluating the financial benefits of combining wind energy with complementary energy storage systems.
- Future work should also focus on studying economic dispatch strategies within the Saudi electricity grid to optimize power generation and improve overall system efficiency.
- Further studies are recommended to compare the impact and cost of various reactive power support applications.

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# Appendices

## A.1 Wind speed Information

**Table 1:** Wind speed data at 100 m and 150 m above various ground levels in 34 cities

| City            | Latitude<br>(°N) | Longitude<br>(°E) | Altitude (m) | Mean Wind Speed |              |
|-----------------|------------------|-------------------|--------------|-----------------|--------------|
|                 |                  |                   |              | (100m) (m/s)    | (150m) (m/s) |
| Aff             | 23.9140          | 42.9110           | 1,048        | 8.13            | 9.22         |
| Al Baha         | 20.0129          | 41.4677           | 2,078        | 7.22            | 8.17         |
| Al Dawadmi      | 24.5076          | 44.3923           | 1,035        | 8.33            | 9.58         |
| Al Hanakiyah    | 24.8500          | 40.5420           | 898          | 6.51            | 8.02         |
| Al Qunfudah     | 19.1264          | 41.0786           | 82           | 4.67            | 4.92         |
| Al Uyaynah      | 24.9074          | 46.3846           | 851          | 6.77            | 8.89         |
| Al Wajh         | 26.2361          | 36.4681           | 46           | 6.28            | 7.05         |
| Arar            | 30.9753          | 41.0231           | 580          | 5.91            | 7.02         |
| Duba            | 27.3519          | 35.6900           | 44           | 6.71            | 7.86         |
| Hafar Al Batin  | 28.4328          | 45.9708           | 358          | 7.46            | 8.23         |
| Jazan           | 16.8892          | 42.5611           | 51           | 4.06            | 4.44         |
| Riyadh          | 24.7743          | 46.7386           | 577          | 4.26            | 5.88         |
| Jeddah          | 21.4925          | 39.1776           | 194          | 6.08            | 6.61         |
| Thuwal          | 22.2723          | 39.1100           | 21           | 5.44            | 5.97         |
| Dammam          | 26.4344          | 50.1033           | 26           | 5.19            | 6.37         |
| Al Ahsa         | 25.3833          | 49.5833           | 212          | 5.74            | 6.41         |
| Al Ghat         | 26.0373          | 43.6800           | 797          | 8.38            | 9.04         |
| Al Kharj        | 24.1554          | 47.3346           | 471          | 5.04            | 6.29         |
| Najran          | 17.4917          | 44.1322           | 1,652        | 4.85            | 5.54         |
| Qassim          | 26.3333          | 43.9667           | 649          | 5.07            | 6.71         |
| Rania           | 21.2500          | 42.8500           | 933          | 6.82            | 8.52         |
| Yanbu           | 24.0895          | 38.0618           | 671          | 6.77            | 9.29         |
| Al Khafji       | 28.4075          | 48.4948           | 67           | 7.72            | 8.43         |
| Farrasan        | 16.7014          | 42.0973           | 18           | 4.96            | 5.68         |
| Neom            | 28.1989          | 34.6892           | 1,234        | 7.61            | 8.38         |
| Umlij           | 25.0500          | 37.2667           | 183          | 6.17            | 7.02         |
| Al Jubail       | 27.0000          | 49.6544           | 31           | 6.56            | 7.76         |
| Shagra          | 25.2582          | 45.2473           | 702          | 6.88            | 8.5          |
| Tabuk           | 28.3972          | 36.5789           | 838          | 4.27            | 5.89         |
| Taif            | 21.4373          | 40.5127           | 1,662        | 6.59            | 7.73         |
| Timaa           | 27.6156          | 38.5455           | 864          | 4.54            | 5.44         |
| Wadi Addawasir  | 20.4643          | 44.7777           | 744          | 7.21            | 8.25         |
| Turaif          | 31.6725          | 38.6631           | 848          | 7.15            | 8.28         |
| Dumat Al Jandal | 29.8103          | 39.8683           | 787          | 7.21            | 8.87         |



## A.2 list of conventional generators displaced by wind turbine farms

**Table 2:** List of the displaced conventional generators for 20% wind power turbines penetration level

| Bus Number | Bus Name     | Operation Region | Pen (MW) |
|------------|--------------|------------------|----------|
| 131        | JEDDAH(SWCC) | WOR              | 800.5    |
| 142        | SHAIBA 2     | WOR              | 800.5    |
| 204        | JUBAIL(SWCC) | EOR              | 151.5    |
| 206        | ARAMCO       | EOR              | 404      |
| 212        | QAISUMAH     | EOR              | 99.7     |
| 213        | MARAFIQ JUBA | EOR              | 2827     |
| 216        | ARAMCO PP10  | COR              | 1496     |
| 234        | RAS KHAIR    | COR              | 1319.4   |
| 307        | WADIALDAWAS  | COR              | 1469     |
| 335        | QASSIM CENTR | COR              | 491      |
| 354        | RIYADH       | COR              | 491      |
| 413        | SHUQIQ(SWCC) | SOR              | 931      |
| 509        | TURAIF       | NOR              | 199.5    |
| 520        | QURYAAT      | NOR              | 199.5    |
| 521        | RAFHA        | NOR              | 299      |
| 538        | TABOUK 1     | NOR              | 956      |

**Table 3:** List of the displaced conventional generators for 40% wind power turbines penetration level

| Bus Number | Bus Name     | Operation Region | Pen (MW) |
|------------|--------------|------------------|----------|
| 112        | TAIF         | WOR              | 855.5    |
| 115        | JEDDAH SOUTH | WOR              | 855.5    |
| 116        | YNBU (SWCC)  | WOR              | 855.5    |
| 131        | JEDDAH(SWCC) | WOR              | 855.5    |
| 140        | SHAIBA 1     | WOR              | 800.5    |
| 142        | SHAIBA 2     | WOR              | 800.5    |
| 203        | FARAS        | EOR              | 2827     |
| 204        | JUBAIL(SWCC) | EOR              | 151.5    |
| 206        | ARAMCO       | EOR              | 404      |
| 207        | HAJJR        | EOR              | 1414.8   |
| 212        | QAISUMAH     | EOR              | 99.7     |
| 213        | MARAFIQ JUBA | EOR              | 2827     |
| 216        | ARAMCO PP10  | EOR              | 1496     |
| 234        | RAS KHAIR    | EOR              | 1319.4   |
| 239        | ALKHOBAR     | EOR              | 1979.2   |
| 307        | WADIALDAWAS  | COR              | 1469     |
| 308        | HAIL 2       | COR              | 491      |
| 317        | PP5          | COR              | 491      |
| 335        | QASSIM CENTR | COR              | 491      |
| 354        | RIYADH       | COR              | 491      |
| 412        | SHUQIQ(SWCC) | SOR              | 2210     |
| 413        | SHUQIQ(SWCC) | SOR              | 931      |
| 415        | JAZAN        | SOR              | 99.7     |
| 509        | TURAIF       | NOR              | 199.5    |
| 520        | QURYAAT      | NOR              | 199.5    |
| 521        | RAFHA        | NOR              | 299      |
| 538        | TABOUK 1     | NOR              | 956      |

**Table 4:** List of the displaced conventional generators for 60% wind power turbines penetration level

| Bus Number | Bus Name     | Operation Region | Pen (MW) |
|------------|--------------|------------------|----------|
| 101        | RABIGH IWSP  | WOR              | 855.5    |
| 112        | TAIF         | WOR              | 855.5    |
| 115        | JEDDAH SOUTH | WOR              | 855.5    |
| 116        | YNBU (SWCC)  | WOR              | 855.5    |
| 120        | RABIGH       | WOR              | 855.5    |
| 123        | MADINAH      | WOR              | 855.5    |
| 131        | JEDDAH(SWCC) | WOR              | 855.5    |
| 137        | OMLEJ        | WOR              | 800.5    |
| 140        | SHAIBA 1     | WOR              | 800.5    |
| 141        | SHAIBA       | WOR              | 800.5    |
| 142        | SHAIBA 2     | WOR              | 800.5    |
| 163        | RABIGH       | WOR              | 1795     |
| 203        | FARAS        | EOR              | 2827     |
| 204        | JUBAIL(SWCC) | EOR              | 151.5    |
| 206        | ARAMCO       | EOR              | 404      |
| 207        | HAJJR        | EOR              | 1414.8   |
| 208        | SHEDGUM      | EOR              | 642      |
| 212        | QAISUMAH     | EOR              | 99.7     |
| 213        | MARAFIQ JUBA | EOR              | 2827     |
| 216        | ARAMCO PP10  | EOR              | 1496     |
| 234        | RAS KHAIR    | EOR              | 1319.4   |
| 239        | ALKHOBAR     | EOR              | 1979.2   |
| 303        | PP8          | COR              | 1964.9   |
| 306        | HAIL 1       | COR              | 491      |
| 307        | WADIALDAWAS  | COR              | 1469     |
| 308        | HAIL 2       | COR              | 491      |
| 315        | PP7          | COR              | 491      |
| 321        | KAPSARC      | COR              | 491      |
| 332        | BURAIDAH     | COR              | 1473     |
| 335        | QASSIM CENTR | COR              | 491      |
| 354        | RIYADH 1     | COR              | 491      |
| 411        | ASIR         | SOR              | 80       |
| 412        | SHUQIQ(SWCC) | SOR              | 2210     |

**Table 5:** Continued on the next page for list of 60% wind power turbines penetration level

| Bus Number | Bus Name     | Operation Region | Pen (MW) |
|------------|--------------|------------------|----------|
| 413        | SHUQIQ(SWCC) | SOR              | 931      |
| 415        | JAZAN        | SOR              | 99.7     |
| 417        | ALBAHA       | SOR              | 99.7     |
| 417        | ALBAHA       | SOR              | 170      |
| 419        | SHAROURA     | SOR              | 147      |
| 443        | JEZAN        | SOR              | 89.2     |
| 509        | TURAIF       | NOR              | 199.5    |
| 513        | JOUF         | NOR              | 199.5    |
| 520        | QURYAAT      | NOR              | 199.5    |
| 521        | RAFHA        | NOR              | 299      |
| 525        | JOUF         | NOR              | 300      |
| 529        | WAJH         | NOR              | 526.4    |
| 532        | DUBA         | NOR              | 299.3    |
| 538        | TABOUK 1     | NOR              | 956      |

**Table 6:** List of the displaced conventional generators for 75% wind power turbines penetration level

| Bus Number | Bus Name                 | Operation Region | Pen (MW) |
|------------|--------------------------|------------------|----------|
| 101        | RABIGH IWSP              | WOR              | 855.5    |
| 104        | RABIGH P/P               | WOR              | 855.5    |
| 112        | TAIF                     | WOR              | 855.5    |
| 113        | YANBU (SEC)              | WOR              | 855.5    |
| 115        | JEDDAH <sub>S</sub> OUTH | WOR              | 855.5    |
| 116        | YNBU (SWCC)              | WOR              | 855.5    |
| 120        | RABIGH                   | WOR              | 855.5    |
| 123        | MADINAH                  | WOR              | 855.5    |
| 128        | MAKKAH                   | WOR              | 855.5    |
| 131        | JEDDAH(SWCC)             | WOR              | 855.5    |
| 137        | OMLEJ                    | WOR              | 800.5    |
| 140        | SHAIBA 1                 | WOR              | 800.5    |
| 141        | SHAIBA                   | WOR              | 800.5    |
| 142        | SHAIBA 2                 | WOR              | 800.5    |
| 143        | MADINAH PP1              | WOR              | 800.5    |
| 163        | RABIGH                   | WOR              | 1795     |
| 203        | FARAS                    | EOR              | 2827     |
| 204        | JUBAIL(SWCC)             | EOR              | 151.5    |
| 206        | ARAMCO                   | EOR              | 404      |
| 207        | HAJJR                    | EOR              | 1414.8   |
| 208        | SHEDGUM 13.800           | EOR              | 642      |
| 209        | ARAMCO PP16              | EOR              | 808      |
| 212        | QAISUMAH                 | EOR              | 99.7     |
| 213        | MARAFIQ JUBA             | EOR              | 2827     |
| 216        | ARAMCO PP10              | EOR              | 1496     |
| 220        | JUYMAH                   | EOR              | 659.7    |
| 234        | RAS KHAIR                | EOR              | 1319.4   |
| 239        | ALKHOBAR                 | EOR              | 1979.2   |
| 300        | PP4                      | COR              | 982.4    |
| 303        | PP8                      | COR              | 1964.9   |
| 306        | HAIL 1                   | COR              | 491      |
| 307        | WADIALDAWAS              | COR              | 1469     |
| 308        | HAIL 2                   | COR              | 491      |

**Table 7:** Continued on the next page for list of 75% wind power turbines penetration level

| Bus Number | Bus Name     | Operation Region | Pen (MW) |
|------------|--------------|------------------|----------|
| 315        | PP7          | COR              | 491      |
| 317        | PP5          | COR              | 491      |
| 321        | KAPSARC      | COR              | 491      |
| 327        | PP4          | COR              | 491      |
| 332        | BURAIDAH     | COR              | 1473     |
| 335        | QASSIM CENTR | COR              | 491      |
| 354        | RIYADH 1     | COR              | 1201     |
| 354        | RIYADH 2     | COR              | 491      |
| 407        | TIHAMA       | SOR              | 80       |
| 411        | ASIR         | SOR              | 80       |
| 412        | SHUQIQ(SWCC) | SOR              | 2210     |
| 413        | SHUQIQ(SWCC) | SOR              | 931      |
| 413        | SHUQIQ(SWCC) | SOR              | 1931     |
| 415        | JAZAN        | SOR              | 99.7     |
| 417        | ALBAHA       | SOR              | 99.7     |
| 417        | ALBAHA       | SOR              | 170      |
| 419        | SHAROURA     | SOR              | 147      |
| 421        | BISHA        | SOR              | 170      |
| 443        | JEZAN        | SOR              | 89.2     |
| 509        | TURAIIF      | NOR              | 199.5    |
| 511        | ARAR         | NOR              | 450      |
| 513        | JOUF         | NOR              | 199.5    |
| 520        | QURYAAT      | NOR              | 199.5    |
| 521        | RAFHA        | NOR              | 299      |
| 525        | JOUF         | NOR              | 300      |
| 529        | WAJH         | NOR              | 526.4    |
| 532        | DUBA         | NOR              | 299.3    |
| 538        | TABOUK-1     | NOR              | 956      |

# Vita

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