

**TRANSIENT AND STEADY-STATE STABILITY ANALYSIS OF SOLAR  
PV- WIND GRID-TIE HYBRID SYSTEM**

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A Thesis submitted to Masinde Muliro University of Science and Technology,  
School of Engineering and Built Environment, in partial fulfillment of the  
requirements for the award of Master of Science in Electrical Engineering

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**DECLARATION**

**DECLARATION BY THE STUDENT**

This Thesis entitled “**Transient and Steady-State Stability Analysis of Solar PV-Wind Grid-Tie Hybrid System**” is my original work, except where due acknowledgment is made in the text and to the best of my knowledge has not been previously submitted for the award of a degree in this or any other university.

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## **DEDICATION**

To my beloved parents, I deeply appreciate their unconditional love and support, which have made this achievement possible. Their unwavering belief in me has been a constant source of inspiration.

To my dearest Naomi Maliro, whose companionship, encouragement, and understanding have been invaluable throughout this journey.

To my mentor, Dr. Cedric Okinda, who has guided and inspired me to reach new heights.

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## ABSTRACT

The global energy landscape is rapidly evolving towards increased reliance on renewable energy sources, driven by concerns over climate change and the finite nature of fossil fuels. However, the integration of variable and intermittent renewable energy sources into the electricity grid presents significant challenges to grid stability and reliability. This study presents a comparative analysis of Solar PV-Wind HRES Grid-Tied System and Solar PV-Wind-Battery HRES Grid-Tied System based on transient and steady-state stability analysis. The systems were simulated using the Electrical Transient Analyzer Program (ETAP®) and Grid-tied to an IEEE 14-bus system. For transient analysis, two common grid disturbances were explored, i.e., Line to Ground faults on buses and faults on the transmission line at different fault positions i.e., 0%, 10%, 25%, 50%, 75%, 90%, and 100% with a fault clearance time of 1.05 s, 1.50 s, and 2.00 s, and the fault set to occur at 1.00 s with a simulation time of 50 s. For steady-state stability, irradiation and wind speed were gradually varied, and Eigenvalue Analysis was performed to assess the dynamic stability of the power system under steady-state conditions. Lastly, ANOVA analysis was performed to analyze the effects of fault position on a transmission line, fault clearance time, and the presence of a battery energy system on the system settling time after a fault occurred based on generator speed, voltage, and frequency. For the Solar PV-Wind HRES Grid-Tied System, it was established that the voltage and frequency profiles at the Bus with the fault dropped significantly during the fault but recovered to their pre-fault level after the fault was cleared for all the explored fault clearance-time. However, a larger fault clearance time (2.00 s) had a longer settling time. Additionally, the eigenvalue analysis established that all eigenvalues were located in the left half of the complex plane, indicating a stable system. Furthermore, there were statistically significant differences between the explored fault clearance times. For the Solar PV-Wind-Battery HRES Grid-Tied System, it was established that the BESS enhanced the stability and efficiency of an HRES with voltages ranging from 0.98772 to 1.000 p.u. Additionally, there was a statistically significant interaction between the effects of fault clearance time and battery on the settling time for voltage, frequency, and generator speed. In comparison, the settling time for the Solar PV-Wind-Battery HRES Grid-Tied System was lower than that for the Solar PV-Wind HRES Grid-Tied System. Therefore, the battery energy system effectively compensates for the inherent variability of renewable energy sources, preventing cascading failures and ensuring system robustness. Additionally, to further improve the performance of the Solar PV-Wind-Battery HRES Grid-Tied System, the implementation of adaptive control strategies such as real-time dynamic droop control or predictive battery dispatch algorithms is recommended. These strategies can enhance the responsiveness of the BESS during fault events, reduce overshoot and oscillations, and ensure faster system stabilization, especially under high-variability renewable input conditions.

## LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

AC	Alternating Current
ANOVA	Analysis Of Variance
BESS	Battery Energy Storage Systems
DAE	Differential-Algebraic Equation
DC	Direct Current
DFIG	Doubly-Fed Induction Generator
DR	Demand Response
ETAP	Electrical Transient Analyzer Program
FACTS	Flexible AC Transmission Systems
$f$	Frequency
$F_p$	Fault Position
GHG	Greenhouse Gas
$G_s$	Generator Speed
GW	Gigawatts
HRES	Hybrid Renewable Energy System
IEEE	Institute Of Electrical And Electronics Engineers
$I_r$	Solar Irradiance
Kw	Kilowatt
Kva	Kilo-Volt-Ampere
LG	Line-To-Ground
MPPT	Maximum Power Point Tracking

MVA	Mega-Volt-Ampere
PCC	Point Of Common Coupling
p.u.	Per Unit
PV	Photovoltaic
PSS	Power System Stabilizers
RTDS	Real Time Digital Simulator
S	Seconds
$S_w$	Wind Speed
$t_s$	Setting Time
SMIB	Single Machine Infinite Bus
SPSS	Statistical Package For The Social Sciences
$t_{ct}$	Fault Clearance Time
V	Voltages
VSI	Voltage Stability Index
WECS	Wind Energy Conversion Systems

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# CHAPTER ONE

## INTRODUCTION

### 1.1. Background

Currently, there has been an increase in the integration of large-scale renewable energy sources (RESs) in power systems due to the concerns wrought by climate change, energy security, and sustainable development (IPCC, 2018; Medina et al., 2022; Newell et al., 2021). Among these renewables, Solar Photovoltaic (PV) and Wind energy have emerged as prominent contributors to the energy mix, owing to their abundant availability, declining costs, and environmentally friendly attributes (Hassan et al., 2024; IRENA, 2020; Kabeyi & Olanrewaju, 2022). Renewable electricity capacity reached 507 GW in 2023, with Solar PV and Wind power accounting for about 96% (CELIK, 2021). Additionally, the renewable generation capacity is projected to double by 2028 to about 710 GW (Mehra et al., 2021). However, the integration of these variable and intermittent renewable energy sources into the electricity grid presents significant challenges to grid stability and reliability (Alam et al., 2020; Basit et al., 2020; Ourahou et al., 2020; Sinsel et al., 2020).

The stability of a power system is its ability to maintain synchronous operation and deliver power to consumers within acceptable voltage and frequency limits under steady-state and transient conditions (Flynn et al., 2019; Machowski et al., 2020; Shair, Li, et al., 2021). Transient stability relates to the system's ability to maintain synchronism following large disturbances such as faults, sudden changes in load, or the loss of generation (Khadka et al., 2020; Shair, Li, et al., 2021). On the other hand, steady-state stability concerns the long-term equilibrium of the system, ensuring that power flows remain balanced and voltage levels are within acceptable limits (Shair,

Li, et al., 2021). Both transient and steady-state stability are essential for the reliable and efficient operation of power systems, including renewable energy integration (He et al. , 2019).

As forementioned, the integration of solar PV and wind power into the electricity grid presents unique challenges due to their inherent variability and intermittency. Unlike conventional fossil fuel-based power plants, which can be dispatched on demand, Solar PV and Wind energy generation are dependent on the time of day and weather conditions (Rehmani et al., 2018). This variability introduces uncertainty into the grid and can lead to operational challenges such as voltage fluctuations, frequency deviations, and power imbalances (Bessa et al., 2019). To address these challenges and ensure the reliable and stable operation of the grid, there is a growing interest in hybrid systems that combine multiple renewable energy sources with complementary characteristics.

Solar PV-Wind grid-tie hybrid systems combine the intermittent nature of solar and wind resources with grid-tied operation to supply electricity to consumers while maintaining a connection to the utility grid (Akinyele et al., 2024). These hybrid systems typically consist of solar PV arrays, wind turbines, power electronics (e.g., inverters), energy storage devices, and grid interconnection points (Akinyele et al., 2024; Rekioua & Rekioua, 2020). During periods of excess renewable generation, surplus energy can be exported to the grid, while during low generation periods, power can be imported from the grid to meet demand. This bidirectional power flow poses unique stability challenges that must be addressed to ensure the reliable operation of the hybrid system and grid compatibility (Ahmed et al., 2020; Amrr et al., 2020).

Several factors contribute to the stability challenges faced by solar PV-wind grid-tie hybrid systems (Ahmed et al., 2024). Firstly, the inherent variability and unpredictability of solar and wind resources introduce fluctuations in power output, leading to voltage and frequency deviations in the grid (Ahmed et al., 2024; Bessa et al., 2019). Secondly, the dynamic behavior of power electronic converters used in hybrid system components, such as inverters and converters for energy storage devices, can influence system stability (Ahmed et al., 2024; Babu et al., 2020). Additionally, the interaction between renewable generation, energy storage, and grid-connected loads creates complex dynamic responses that require careful analysis and control (Pfeifer et al., 2018).

Stability analysis is crucial for the successful integration of hybrid renewable energy systems into the electrical grid (Stephanie & Karl, 2020). It ensures that the system can withstand disturbances and maintain reliable operation under varying conditions (Sawle et al., 2018; Stephanie & Karl, 2020). Understanding the stability characteristics of hybrid systems can aid in the development of robust control strategies, enhancing the overall performance and reliability of the power supply (Al-Shetwi, Hannan, et al., 2020; Stephanie & Karl, 2020). Moreover, stability analysis can provide valuable insights for grid operators and policymakers, facilitating the implementation of effective regulations and standards for renewable energy integration (Cambini et al., 2020; Martinot, 2016).

Therefore, it is essential to conduct comprehensive transient and steady-state stability analyses of solar PV-wind grid-tie hybrid systems to assess the system's performance under various operating conditions and disturbances to develop effective control strategies and mitigation techniques to enhance system stability and reliability.

## **1.2. Problem statement**

The global energy landscape is rapidly evolving towards increased reliance on sustainable and renewable energy sources, driven by concerns over climate change and the finite nature of fossil fuels. This increasing demand for sustainable and renewable energy sources has led to the widespread adoption of Solar PV and Wind energy systems. As already mentioned, these renewable energy sources offer significant environmental benefits by reducing greenhouse gas emissions (GHG) and dependence on fossil fuels. However, their integration into the power grid presents substantial technical challenges, particularly in terms of maintaining grid stability and reliability (Ahmed et al., 2020; Ourahou et al., 2020). A critical issue that arises from this integration is the stability of hybrid systems that combine Solar PV and Wind energy, especially when these systems are connected to the grid.

Hybrid solar PV-Wind systems leverage the complementary nature of solar and wind resources, enhancing the overall efficiency and reliability of power generation (Roy et al., 2022). Despite their potential, these systems are inherently variable and intermittent, primarily due to the fluctuating nature of solar irradiation and wind speeds. This variability introduces significant challenges in maintaining both the transient and steady-state stability of the power system. The problem of stability worsens as the penetration of solar PV and wind power increases, grid operators face significant challenges in maintaining stable operations due to variability and uncertainty inherent in renewable energy generation (Alam et al., 2020). Fluctuations in solar irradiance and wind speed can lead to rapid changes in power output, causing voltage and frequency fluctuations in the grid (Nirosha & Patra, 2020). These fluctuations can compromise the transient stability of the grid, such as voltage instability, frequency fluctuations, and power oscillations, which may jeopardize the

stability of the grid in terms of power outages, equipment damage, and reduced system efficiency (Nirosha & Patra, 2020).

Transient stability refers to the ability of the power system to remain in synchronism and return to a stable operating condition following a large disturbance, such as a short circuit or sudden loss of generation (Machowski et al., 2020; Pertl et al., 2018). For hybrid solar PV-wind systems, transient stability is particularly critical as disturbances can lead to significant fluctuations in power output, potentially causing system-wide instability (Jamal & Salehin, 2021; Liang et al., 2022). Additionally, the continuous integration of renewable energy into the grid poses challenges in maintaining steady-state stability, especially during periods of low renewable energy generation or high demand. Variations in power output from solar PV and wind turbines can impact grid voltage and frequency stability, potentially leading to voltage deviations and frequency mismatches (Nirosha & Patra, 2020). The rapid and unpredictable changes in output from these renewable sources can induce voltage and frequency deviations, which need to be carefully managed to prevent cascading failures.

Steady-state stability, on the other hand, concerns the power system's ability to maintain equilibrium under normal operating conditions and small perturbations (Alves et al., 2020). In hybrid systems, steady-state stability is challenged by the continuous variation in generation levels (Atawi et al., 2022). The intermittent nature of solar and wind resources requires sophisticated control strategies and energy management systems to ensure a balanced and stable operation (Machowski et al., 2020; Pertl et al., 2018). Without effective stability measures, the integration of these renewable sources could compromise the overall reliability of the power grid.

Current studies highlight several methods to enhance the stability of hybrid renewable energy systems. However, many studies focus on either solar PV or wind systems in isolation, without addressing the unique challenges posed by their combined operation in a grid-tied configuration (Emad et al., 2020). Additionally, the majority of research has been centered on transient stability, with less emphasis on steady-state stability issues specific to hybrid systems (He et al., 2021; Mehta & Basak, 2021; Sobbouhi & Vahedi, 2021; Vadi et al., 2019). This gap in the research underscores the need for a comprehensive stability analysis that considers both transient and steady-state conditions in hybrid solar PV-wind grid-tie systems.

Finally, the integration of these hybrid systems into existing power grids requires advanced modeling and simulation tools to accurately predict and mitigate stability issues. Current simulations often lack the necessary detail and precision to capture the dynamic interactions between solar PV, wind turbines, and the grid, leading to potential oversights in stability analysis (Alnawafah, 2024). Therefore, developing robust models that can simulate the complex behavior of hybrid systems under various operating conditions is essential for ensuring their stable integration into the power grid.

### **1.3. Objectives**

#### **1.3.1. Main objective**

The main objective of the project is to examine the transient and steady-state stability of a Grid-Tie solar PV and wind power hybrid system.

#### **1.3.2. Specific objectives**

1. To develop a detailed and accurate IEEE 14 Bus system model for efficient integration of the solar PV-wind hybrid system.

2. To analyze the transient stability of the hybrid grid-tie system under sudden changes, i.e., faults on transmission lines and buses.
3. To analyze the steady-state stability of the hybrid grid-tie system in response to small, continuous changes in operating conditions, i.e., gradual variations in solar irradiance and wind speed
4. To determine the impact of energy storage systems on the stability and reliability of hybrid grid-tie systems.

#### **1.4. Significance of the Study**

The significance of this study lies in its contribution to the reliable integration of renewable energy sources into the power grid, a critical aspect of modern energy systems. Hybrid solar PV-wind systems offer numerous advantages, including enhanced energy security, reduced greenhouse gas emissions, and improved economic viability (Khan et al., 2021). However, their integration poses significant stability challenges due to the intermittent and variable nature of renewable energy sources.

Understanding and analyzing the transient and steady-state stability of hybrid systems is crucial for ensuring a reliable and continuous power supply. Transient stability analysis helps in understanding the system's behavior during disturbances, such as sudden changes in load or faults, and ensures that the system can return to a stable operating condition. Steady-state stability analysis, on the other hand, focuses on the system's ability to maintain equilibrium under small perturbations, which is essential for long-term operation.

This research contributes to the body of knowledge by providing a comprehensive stability analysis of hybrid solar PV-wind grid-tie systems, addressing both transient and steady-state aspects. By identifying potential stability issues and proposing

solutions, the study aims to enhance the reliability and efficiency of hybrid renewable energy systems. Furthermore, the findings can inform policymakers and engineers in designing and implementing more robust and resilient power systems, ultimately supporting the global transition toward sustainable energy. Thus, this research not only advances academic understanding but also has practical implications for the future of energy infrastructure.

The transition towards renewable energy sources, such as solar PV and wind power, is crucial for mitigating climate change and reducing dependence on finite fossil fuels. However, integrating these intermittent energy sources into the grid presents significant challenges, particularly regarding stability and reliability. Understanding the transient and steady-state stability of grid-tie solar PV and wind power hybrid systems is essential for ensuring the smooth integration of renewable energy into the existing grid infrastructure. By analyzing the stability characteristics of these hybrid systems, we can develop effective control strategies and system design considerations to enhance grid stability and reliability, ultimately facilitating the transition towards a more sustainable energy future.

## **1.5. Scope and Limitations**

### **1.5.1. Scope of the Study**

The primary focus of this research is the transient and steady-state stability analysis of solar PV-wind grid-tie hybrid systems. The study encompasses the following key areas:

1. **System Modeling:** The research involves developing detailed simulation models of solar PV and wind energy systems, and their integration into a grid-tie hybrid configuration. The models will capture the dynamic behavior of both renewable sources and their interactions with the grid.

2. **Stability Analysis:** The core of the research is to analyze the stability of the hybrid system under various operating conditions. This includes both transient stability, which deals with the system's response to sudden disturbances, and steady-state stability, which focuses on the system's ability to maintain equilibrium under normal operating conditions.
3. **Impact of Energy Storage Systems:** The project will also examine the impact of energy storage systems on the stability and reliability of hybrid grid-tie systems. Energy storage plays a crucial role in mitigating the intermittency of renewable energy sources and enhancing grid stability by providing additional flexibility and resilience.

#### **1.5.2. Limitations of the Study**

While this research aims to provide a comprehensive analysis of the stability of solar PV-wind hybrid systems, several limitations are acknowledged:

1. **Model Assumptions:** The accuracy of the stability analysis depends on the assumptions made during the modeling process. Simplifications are necessary to make the simulations feasible, but they may introduce inaccuracies. For instance, the models may not fully capture all the complexities of real-world systems, such as the variability of renewable energy sources and the detailed dynamics of the power grid.
2. **Data Availability:** The validation of simulation results relies on the availability and quality of real-world data. Inadequate or inaccurate data can affect the validity of the findings. Additionally, the study may be constrained by the availability of detailed meteorological data, which is crucial for modeling the performance of solar and wind systems.

3. **Scope of Disturbances:** The study focuses on specific types of disturbances to assess transient stability. However, it may not cover all possible scenarios, such as extreme weather events or rare grid faults, which could impact the stability analysis.
4. **Technological Variability:** The performance and stability of hybrid systems can vary significantly based on the specific technologies and configurations used. The findings of this study are based on particular types of solar PV and wind systems, which may limit their generalizability to other configurations.
5. **Regulatory and Environmental Factors:** The study does not extensively consider the impact of regulatory policies, market conditions, and environmental factors on the stability of hybrid systems. These external factors can play a significant role in the real-world deployment and operation of renewable energy systems.

Despite these limitations, this project aims to provide valuable insights into the stability characteristics of grid-tie solar PV and wind power hybrid systems, ultimately contributing to the development of more resilient and reliable renewable energy infrastructure.

## **1.6. Thesis Structure**

This thesis is outlined as follows: Chapter 1 presents the general introduction to the study. Chapter 2 presents a review of relevant literature within the scope of this study, including an overview of solar PV, Wind power, Grid-Tie Hybrid systems, and Stability in Power Systems, and a review of relevant literature with reference to the specific objectives. Chapter 3 presents the methodology of the research based on the specific objectives, while Chapter 4 presents the research results, analysis, and

discussions. Chapter 5 gives a summary of the research, and conclusions, and gives recommendations based on the obtained results.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1. Introduction

Hybrid renewable energy systems (HRES) are innovative solutions that combine multiple sources of renewable energy, typically PV and wind, to generate electricity in a complementary manner, as shown in Figure 2.1. The integration of different energy sources into a single system helps overcome the intermittency issues associated with renewable energy and enhances the overall reliability and efficiency of energy production (Husin & Zaki, 2021). Thus, the primary objective of an HRES is to ensure continuous and efficient energy production, especially in areas where one renewable resource alone might not be sufficient to meet energy demands consistently (Tezer et al., 2017). By integrating multiple sources, HRES can optimize energy generation, improve system reliability, and reduce dependency on non-renewable energy sources (Babatunde et al., 2020; Tezer et al., 2017).

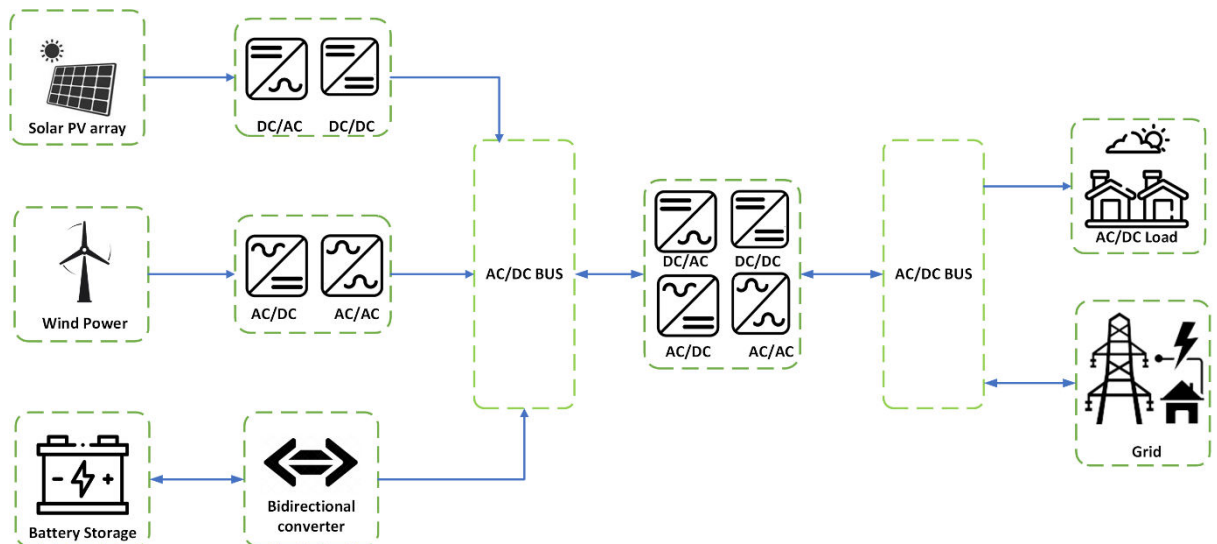


Figure 2.1: A Typical PV and Wind Hybrid Renewable Energy System and components

## **2.2. Historical Development of Hybrid Renewable Energy Systems**

The concept of HRES has evolved significantly over the past few decades (as shown in Figure 2.2), driven by the growing demand for reliable and sustainable energy sources (Khan et al., 2022). The early development of HRES can be traced back to the late 20<sup>th</sup> century when the global energy sector began to explore alternative energy solutions due to the increasing awareness of environmental issues and the limitations of fossil fuels (DGB Group, 2023; Zebra et al., 2021). The 1970s energy crisis was a significant turning point in the history of renewable energy (Fouquet, 2016). The oil embargoes and the resultant energy shortages highlighted the vulnerabilities of relying heavily on fossil fuels (Burke & Stephens, 2018; DGB Group, 2023). This period spurred research and development in alternative energy sources, particularly solar and wind energy (Burke & Stephens, 2018). However, the technology at the time was still in its infancy, and the high costs associated with renewable energy systems limited their widespread adoption (DGB Group, 2023; Fouquet, 2016). During the 1980s and 1990s, advancements in PV technology and wind turbine design led to increased interest in integrating these renewable energy sources (Burke & Stephens, 2018; DGB Group, 2023; Roy et al., 2022). The first hybrid systems were relatively simple, often combining diesel generators with renewable energy sources like solar PV or small wind turbines to provide power in remote locations where grid access was limited (DGB Group, 2023; Lian et al., 2019). These early systems demonstrated the potential of combining different energy sources to improve reliability and reduce fuel consumption (DGB Group, 2023; Lian et al., 2019; Roy et al., 2022).

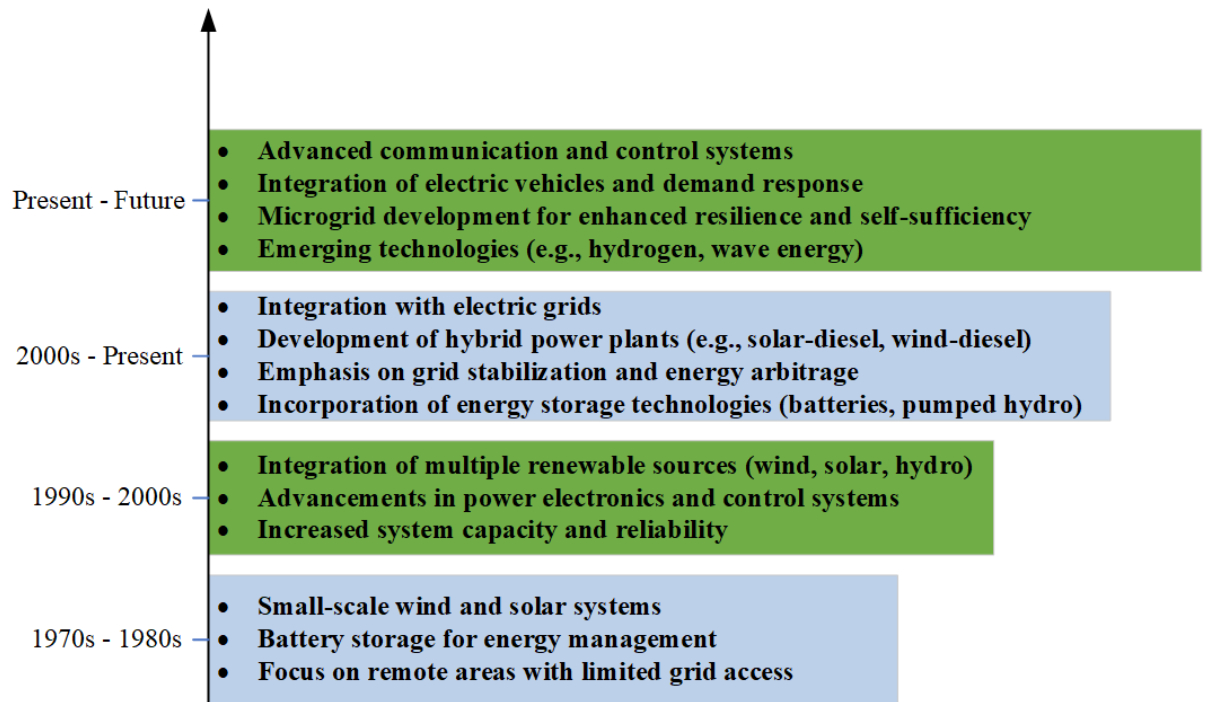


Figure 2.2: Timeline of Hybrid Renewable Energy Systems Development

The 21<sup>st</sup> century marked a significant shift in the development of HRES, driven by the global push for sustainable development and the need to address climate change (Babatunde et al., 2020; Gernaat et al., 2021). Governments and international organizations began to implement policies and incentives to promote renewable energy adoption, leading to increased research and deployment of hybrid systems (Cooper & Sommer, 2016; Sawle et al., 2018). The integration of advanced energy storage systems, such as batteries, into HRES became more common during this period, allowing for greater flexibility and reliability in power generation (Sayed et al., 2023; Yang et al., 2018).

Technological advancements in power electronics, control systems, and energy management also played a crucial role in the evolution of HRES (Rathod & Subramanian, 2022; Wei et al., 2023). These innovations enabled more sophisticated hybrid systems capable of efficiently managing multiple energy sources, optimizing performance, and ensuring grid stability (Kumar et al., 2022; Stephanie & Karl, 2020).

By the 2010s, HRES had evolved from niche applications in remote areas to being considered a viable solution for large-scale energy generation and grid integration (Logesh, 2017).

### **2.3. Components of Hybrid Renewable Energy Systems**

An HRES typically comprises several key components, each playing a crucial role in the overall functionality and efficiency of the system as presented in Figure 2.1. The combination of these components in an HRES allows for a more resilient and efficient energy generation system that can effectively meet the energy demands of various applications (Thirunavukkarasu et al., 2023). As renewable energy technologies continue to advance, the integration and optimization of these components will become increasingly sophisticated, further enhancing the viability and performance of HRES in the global energy landscape (Khan et al., 2022). These components of HRES include:

#### **2.3.1. Renewable Energy Sources**

- **Solar PV Panels:** Solar PV panels are a core component of most HRES setups (Kajela & Manshahia, 2017; Khan et al., 2022). They convert sunlight directly into electricity through the photovoltaic effect (Sampaio & González, 2017). The efficiency of solar PV panels depends on factors such as the quality of the solar cells, the angle of installation, and the availability of sunlight (Fouad et al., 2017). Solar energy is most abundant during the day, making it a valuable component for energy generation, particularly in sunny regions (Hayat et al., 2019).
- **Wind Turbines:** Wind turbines are another critical component of HRES, particularly in areas with consistent wind patterns (Roy et al., 2022). They

generate electricity by converting the kinetic energy of wind into mechanical energy, which is then converted into electrical energy through a generator (Chaudhuri et al., 2022; Wang et al., 2018). Wind energy is typically more available during the night and in cloudy or stormy conditions, complementing the energy generated by solar PV panels during the day (Chaudhuri et al., 2022; Ganthia et al., 2021).

### 2.3.2. Energy Storage Systems

Energy storage systems are essential for balancing supply and demand in an HRES (Yang et al., 2018). They store excess energy generated during periods of high renewable output and release it when energy production is low or demand is high (Amrouche et al., 2016). The most common types of energy storage systems in HRES include:

- **Batteries:** Batteries are the most widely used storage solution in HRES (Tharani & Dahiya, 2018; Yang et al., 2018). They store electrical energy in chemical form and release it when needed (Gao et al., 2022). Lithium-ion batteries are popular due to their high energy density, efficiency, and long life cycle (Gao et al., 2022; Wu et al., 2020).
- **Supercapacitors:** Supercapacitors are used for short-term energy storage and can deliver rapid bursts of energy (Afif et al., 2019; Svasta et al., 2017). They are often used in conjunction with batteries to provide a quick response to sudden changes in energy demand (Dutta et al., 2023; Kularatna & Gunawardane, 2021).

### 2.3.3. Power Electronics and Control Systems

Power electronics and control systems are vital for managing the interaction between the different components of an HRES (Sedaghati & Shakarami, 2019). They ensure that the energy generated by renewable sources is efficiently converted and distributed to meet the load requirements (Souza Junior & Freitas, 2022). The key components of power electronics and control systems include:

- **Inverters:** Inverters convert the direct current (DC) produced by solar PV panels and wind turbines into alternating current (AC), which is used in most electrical grids and appliances (Kopec et al., 2016). Inverters also play a role in managing the power quality and ensuring the stability of the electricity supply (Al-Shetwi, Sujod, et al., 2020).
- **Charge Controllers:** Charge controllers regulate the flow of electricity between renewable energy sources, storage systems, and the grid or load (Tungadio & Sun, 2019). They prevent overcharging or deep discharging of batteries, thus extending their lifespan (Imran et al., 2020; Tungadio & Sun, 2019).
- **Maximum Power Point Tracking (MPPT):** MPPT is a control strategy used to optimize the output of solar PV panels by continuously adjusting the electrical load to ensure the panels operate at their maximum power point under varying conditions (Verma et al., 2016).

### 2.3.4. Auxiliary Components

- **Load Management Systems:** These systems monitor and control the distribution of energy to different loads, ensuring that critical loads receive

priority during periods of limited energy availability (Das et al., 2018; Hosseini et al., 2017).

- **Backup Generators:** In some HRES setups, a backup generator powered by diesel or another non-renewable source may be included to provide additional reliability in extreme conditions where renewable resources are insufficient (Ansari et al., 2023).

## 2.4. Solar PV Systems

Solar PV systems are one of the most widely used renewable energy technologies today, converting sunlight directly into electricity through the photovoltaic effect (Sampaio & González, 2017). These systems have gained significant popularity due to their scalability, reliability, and abundance of solar energy, making them a key component in the transition towards sustainable energy sources (Dambhare et al., 2021; Sampaio & González, 2017). The photovoltaic effect is a process where light photons striking a semiconductor material generate an electric current (Bayod-Rújula, 2019; Honsberg & Bowden, 2024; Ramalingam & Indulkar, 2017) as shown in Figure 2.3. The most common material used in PV cells is silicon, due to its abundant availability and favorable electronic properties (Dambhare et al., 2021; Luceño-Sánchez et al., 2019). When sunlight hits the silicon-based PV cells, it excites electrons, creating electron-hole pairs (Honsberg & Bowden, 2024; Luceño-Sánchez et al., 2019; Mohammad & Mahjabeen, 2023; Ushasree & Bora, 2019). These pairs are then separated by an electric field within the cell, generating a flow of electric current when connected to an external circuit (Baig, 2021; Honsberg & Bowden, 2024; Mohammad & Mahjabeen, 2023; Ushasree & Bora, 2019).

### 2.4.1. Performance Characteristics

The efficiency of a solar PV system is a key performance indicator, defined as the ratio of the electrical output to the solar energy input. Modern commercial PV cells typically have efficiencies ranging from 15% to 22% (Bandaru et al., 2021), though research continues to push these boundaries (Bandaru et al., 2021; Fouad et al., 2017). The efficiency is also temperature-dependent, typically decreasing as the temperature increases (Khan et al., 2016; Silverman et al., 2018; C. Sun et al., 2022). This temperature effect is quantified by the temperature coefficient, which is usually negative for silicon-based PV cells (Khan et al., 2016; Silverman et al., 2018; C. Sun et al., 2022). Another important characteristic is the PV system's power output, which depends on the incident solar radiation (irradiance) measured in watts per square meter ( $\text{W}/\text{m}^2$ ) (Aghaei, 2022). The relationship between the incident light and the output power is linear, meaning that more sunlight results in higher power output (Michael et al., 2020; Peng et al., 2019). However, factors like shading from nearby objects or dirt on the panels can significantly reduce the system's output (Michael et al., 2020; Ramli et al., 2016)

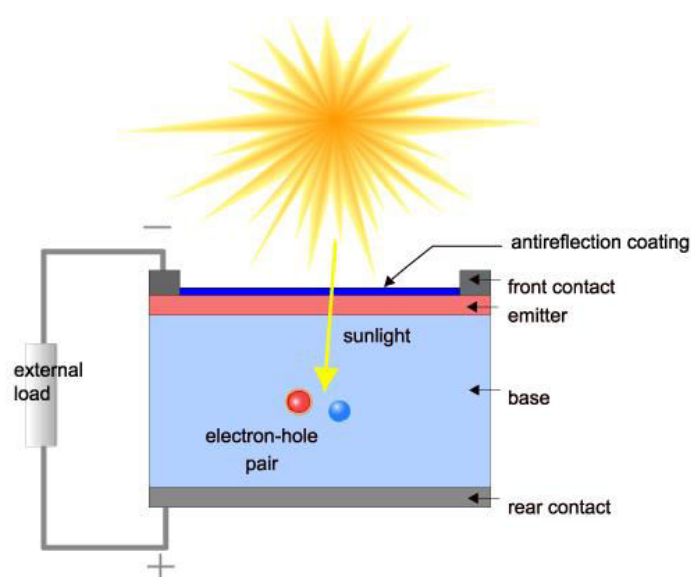


Figure 2.3: The cross-section of a solar cell (Honsberg & Bowden, 2024)

### 2.4.2. Modeling of Solar PV Systems

The modeling of solar PV systems is crucial for predicting their performance under various environmental conditions and optimizing their design (Alsadi & Khatib, 2018). The most common approach involves using an equivalent circuit model, which represents the PV cell as a current source with a diode and resistive elements (Aouchiche et al., 2018) as given in Figure 2.4. This model captures the nonlinear relationship between the voltage and current of the PV cell, known as the I-V curve, which is essential for understanding the system's behavior under different operating conditions (Aouchiche et al., 2018).

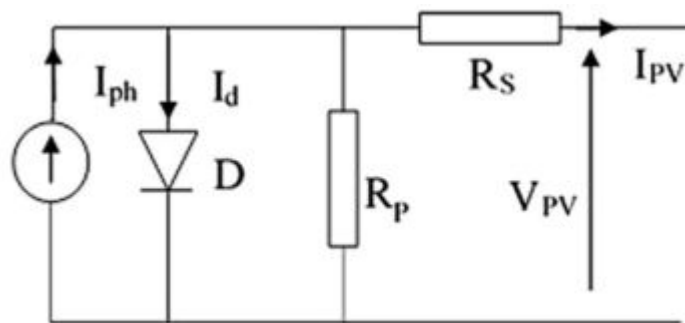


Figure 2.4: The equivalent circuit model of a PV cell

Studies such as Robles–Campos et al. (2019), Ghabuzyan et al. (2021), Premkumar et al. (2020), Kermadi et al. (2020), and Al-Masrani & Al-Obaidi (2019) have introduced advanced models that also consider temperature effects, shading, and other dynamic factors to provide a more accurate representation of the PV system's performance. These models are integral to the design and optimization of solar PV systems, ensuring they operate efficiently and reliably across varying conditions (Aslam et al., 2022; Ehtesham & Jamil, 2021; Hofer et al., 2016).

### 2.4.3. Types of Solar PV Systems and Applications

A typical solar PV system consists of several key components, including PV modules (or panels), an inverter, a mounting structure, and, in some cases, an energy storage

system (Aghaei, Kumar, et al., 2020; Malinowski et al., 2019). The PV modules are made up of multiple interconnected PV cells, which together produce direct current (DC) electricity (Şahin & Okumuş, 2016). Since most appliances and grid systems operate on alternating current (AC), the inverter is essential for converting the DC output of the PV modules into usable AC power (Shneen & Hussein, 2018). Solar PV systems can be broadly categorized into three types: grid-tied, off-grid, and hybrid systems (Kumar et al., 2017). Grid-tied PV systems are directly connected to the electricity grid, allowing for the exchange of electricity between the system and the grid (Anzalchi & Sarwat, 2017). These systems are designed to provide power to the grid when excess energy is produced and draw power from the grid when the solar output is insufficient to meet demand (Yanine et al., 2020). Net metering is a common practice with grid-tied systems, where surplus electricity sent to the grid is credited to the system owner's account, reducing their overall energy costs (Afonaa-Mensah et al., 2024; Rehman et al., 2020). Off-grid PV systems, on the other hand, are not connected to the grid and typically rely on battery storage to provide power when solar energy is not available, such as during the night or on cloudy days (Algaddafi et al., 2016; de Almeida et al., 2020). These systems are often used in remote areas where grid access is unavailable or unreliable (de Almeida et al., 2020; Feron, 2016). Hybrid PV systems combine both grid-tied and off-grid features, integrating battery storage with grid connectivity (Perdana et al., 2018). These systems provide greater flexibility by allowing the use of stored energy during grid outages or peak demand periods, while still benefiting from the ability to export excess energy to the grid (Hajiaghahi et al., 2019).

Solar PV systems have a wide range of applications, from small-scale residential installations to large utility-scale solar farms (Aghaei, Eskandari, et al., 2020; Wolfe,

2018). Residential PV systems are typically installed on rooftops, providing households with a renewable source of electricity that can significantly reduce energy bills and carbon footprints (Deng & Newton, 2017; Goldstein et al., 2020). Commercial and industrial installations are similar on a larger scale, often used to power businesses and factories, contributing to corporate sustainability goals (Choudhary & Srivastava, 2019). Utility-scale solar farms consist of large arrays of PV panels that generate electricity for distribution through the grid, supplying power to thousands of homes and businesses (Einstein, 2020). These large-scale installations play a crucial role in national and regional efforts to increase the share of renewable energy in the overall energy mix (Daniels, 2023; Einstein, 2020).

Solar PV systems offer numerous advantages, including the ability to generate clean, renewable energy with minimal environmental impact (Tawalbeh et al., 2021). Unlike fossil fuels, solar energy production does not produce greenhouse gases or other pollutants, making it a key technology in combating climate change (Ebhota & Jen, 2020). Additionally, solar PV systems have low operational and maintenance costs, as they have no moving parts and can operate for decades with minimal intervention (Pandey et al., 2016). However, there are challenges associated with solar PV systems. As already mentioned, one of the primary challenges is the intermittency of solar energy, as the amount of sunlight varies throughout the day and is affected by weather conditions (Al-Shahri et al., 2021). This intermittency necessitates the use of energy storage or backup power sources to ensure a consistent energy supply (Wu et al., 2022). Furthermore, the initial capital cost of PV systems can be high, although this has been decreasing steadily due to technological advancements and economies of scale (Xin-gang & Zhen, 2019).

## 2.5. Wind Energy Systems

Wind energy systems have also become a crucial component of the global energy landscape, offering a sustainable and renewable alternative to fossil fuels (Zohuri, 2023). As one of the fastest-growing sources of electricity generation, wind energy harnesses the kinetic energy of wind to produce electricity (Kumar et al., 2016; Zohuri, 2023).

### 2.5.1. Basic Principles and Components

Wind energy systems operate on the fundamental principle of converting the kinetic energy of wind into mechanical energy, which is then transformed into electrical energy (Chaudhuri et al., 2022). This process occurs through several key components, each playing a critical role in the efficient conversion of wind power (Blaabjerg & Ma, 2017; Chaudhuri et al., 2022; Rekioua, 2024) as shown in Figure 2.5.

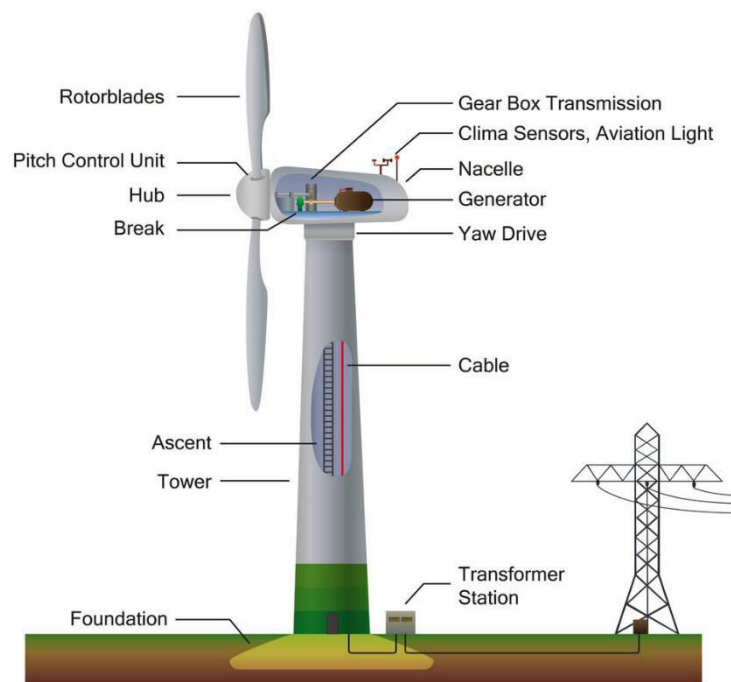


Figure 2.5: An illustration of the typical components of a wind power generator (Green Rhino Energy, 2024)

**Wind Turbine Rotor:** The rotor is the primary component responsible for capturing wind energy. It consists of multiple blades that are aerodynamically designed to

maximize energy capture from the wind (Jamieson, 2018; Schmitz, 2020). When wind flows over the blades, it creates a pressure difference, causing the blades to rotate (Schmitz, 2020). The rotation of the rotor generates mechanical energy, which is transferred to the turbine's generator (Jamieson, 2018).

**Nacelle:** The nacelle is the housing located at the top of the wind turbine tower that contains critical components, including the gearbox, generator, and control systems (Márquez et al., 2016; McKenna et al., 2016). The gearbox increases the rotational speed of the rotor to a level suitable for electricity generation, while the generator converts the mechanical energy into electrical energy (McKenna et al., 2016; Nejad et al., 2022)

**Generator:** The generator is a crucial component that converts mechanical energy into electrical energy (McKenna et al., 2016). There are different types of generators used in wind turbines, including asynchronous (induction) generators and synchronous generators (Babu & Divya, 2017). The choice of generator depends on factors such as the size of the turbine and the specific requirements of the wind energy system (Babu & Divya, 2017; Ganthia et al., 2022)

**Tower:** The tower supports the nacelle and rotor, elevating them to a height where wind speeds are higher and more consistent (Wang et al., 2017). The height of the tower is a critical factor in the overall efficiency of the wind turbine, as wind speed increases with altitude (Guo et al., 2021; Wass, 2018)

**Yaw Mechanism:** The yaw mechanism allows the nacelle to rotate horizontally to face the wind direction (Micallef & Sant, 2016). This ensures that the rotor is always aligned with the wind, maximizing energy capture (Micallef & Sant, 2016; Solomin et al., 2022). Modern wind turbines are equipped with automated yaw systems that

continuously adjust the nacelle's orientation based on wind direction (Solomin et al., 2022; Yang et al., 2021)

**Control Systems:** Control systems play a vital role in optimizing the performance and safety of wind turbines (Gao & Liu, 2021). These systems monitor various parameters, such as wind speed, rotor speed, and power output, and adjust the turbine's operation accordingly (Apata & Oyedokun, 2020). For example, control systems can adjust the pitch angle of the blades to optimize energy capture or activate braking systems to prevent damage during high winds (Song et al., 2018)

**Foundation:** The foundation anchors the wind turbine to the ground, providing stability and support (Lavanya & Kumar, 2020; Manzano-Agugliaro et al., 2020). The design of the foundation depends on factors such as soil conditions, turbine size, and local environmental factors (Guo et al., 2021). Common foundation types include shallow and deep foundations, depending on the site's geotechnical properties (Guo et al., 2022).

### 2.5.2. Performance Characteristics

The performance of a wind energy system is influenced by several factors, including wind speed, turbine design, and environmental conditions (Bashir, 2022).

**Wind Speed and Power Output:** Wind speed is the most critical factor influencing the performance of a wind turbine (Sohoni et al., 2016). The power output of a turbine is proportional to the cube of the wind speed (Sohoni et al., 2016) as given in Eq. 2.1. Therefore, a small increase in wind speed leads to a significant increase in power output (Sohoni et al., 2016; Wang et al., 2016). The relationship between wind speed and power output is typically represented by a power curve, which shows the turbine's power output at different wind speeds (Pelletier et al., 2016).

$$P = \frac{1}{2} \rho A v^3 C_p \quad (2.1)$$

Where  $P$  is the power output,  $\rho$  is the air density,  $A$  is the swept area of the rotor blades,  $v$  is the wind speed, and  $C_p$  is the power coefficient

**Cut-in, Rated, and Cut-out Wind Speeds:** Wind turbines operate within specific wind speed ranges (Porté-Agel et al., 2020; Wilson & Lissaman, 2018). The cut-in wind speed is the minimum speed at which the turbine begins to generate electricity (Astolfi et al., 2018). The rated wind speed is the speed at which the turbine produces its maximum power output (Sedaghat et al., 2017). The cut-out wind speed is the maximum speed at which the turbine can safely operate; beyond this speed, the turbine shuts down to prevent damage (Astolfi et al., 2018; Swisher et al., 2022).

**Capacity Factor:** The capacity factor is a measure of how efficiently a wind turbine operates over time (Pfaffel et al., 2017). It is defined as the ratio of the actual energy produced by the turbine to the energy it could have produced if it operated at full capacity continuously (Pfaffel et al., 2017; Sohoni et al., 2016). Capacity factors typically range from 20% to 40%, depending on factors such as wind speed variability and turbine design (Miller & Keith, 2018; Sohoni et al., 2016).

**Aerodynamic Efficiency:** The aerodynamic efficiency of a wind turbine is a measure of how effectively the rotor blades convert the kinetic energy of the wind into mechanical energy (Adeyeye et al., 2021; Chaudhuri et al., 2022). This efficiency is influenced by the blade design, including the shape, angle, and material of the blades (Adeyeye et al., 2021). The Betz limit (Ranjbar et al., 2019), a theoretical maximum efficiency of 59.3%, represents the upper limit of aerodynamic efficiency for wind turbines (Kramm et al., 2016; Ranjbar et al., 2019).

**Noise and Vibration:** Noise and vibration are yet another important performance characteristic, particularly in wind turbines located near residential areas (Liu, 2017; van Kamp & van den Berg, 2018). Noise is generated by the interaction between the rotor blades and the air, as well as by mechanical components such as the gearbox (Xu et al., 2021). Additionally, vibration can affect the structural integrity of the turbine and its foundation, making it a critical factor in the design and maintenance of wind energy systems (Xu et al., 2021).

### 2.5.3. Modeling of Wind Energy Systems

Similarly, accurate modeling of wind energy systems is essential for optimizing their performance, predicting energy output, and assessing their economic viability. Various modeling techniques are used to simulate different aspects of wind turbines, including aerodynamic performance (Hand & Cashman, 2018), structural dynamics (Prajapat et al., 2017), and energy yield (Thé & Yu, 2017).

**Aerodynamic Modeling:** Aerodynamic models simulate the interaction between the wind and the rotor blades, providing insights into the forces and torques acting on the blades (Ju & Sun, 2017). The Blade Element Momentum (BEM) theory (Özkan & Genç, 2023) is one of the most widely used aerodynamic models for wind turbines. It divides the rotor blade into small elements and calculates the lift and drag forces on each element to determine the overall aerodynamic performance of the turbine (Özkan & Genç, 2023; Z. Sun et al., 2016). Computational Fluid Dynamics (CFD) (Calautit et al., 2018) is another powerful tool for aerodynamic modeling, allowing for detailed simulations of airflow around the turbine blades and nacelle (Calautit et al., 2018; Rajamohan et al., 2022; Tucker, 2016)

**Structural Dynamics Modeling:** Structural dynamics models simulate the mechanical behavior of wind turbines, including the response to loads such as wind forces, gravity, and rotor imbalance (Jahani et al., 2022; Xie & Aly, 2020). These models are critical for assessing the structural integrity of the turbine and its components, as well as for designing control systems to mitigate the effects of dynamic loads (Jahani et al., 2022). Finite Element Analysis (FEA) (Szabó & Babuška, 2021) is commonly used for structural dynamics modeling, providing detailed insights into stress, strain, and deformation in the turbine's structure (Blasques et al., 2016; Jahani et al., 2022).

**Energy Yield Prediction:** Energy yield models predict the amount of electricity a wind turbine will generate over a given period (Barbosa de Alencar et al., 2017). These models take into account factors such as wind speed distribution, turbine power curve, and site-specific conditions (Barbosa de Alencar et al., 2017). The Weibull distribution is often used to model wind speed variability, providing a statistical representation of wind speeds at a given location. By combining the Weibull distribution (Kızılersü et al., 2018) with the turbine's power curve, energy yield models can estimate the expected energy output of the turbine (Akgül et al., 2016; Wais, 2017)

**Economic Modeling:** Economic models assess the financial viability of wind energy projects by considering factors such as capital costs, operation and maintenance costs, energy yield, and revenue from electricity sales (de Oliveira Azevêdo et al., 2021; Keeley & Managi, 2019; Rocha et al., 2018). These models are essential for determining the Levelized Cost of Energy (LCOE), which represents the average cost per unit of electricity generated by the wind turbine over its lifetime (Bruck et al., 2016, 2018). Sensitivity analysis is often used in economic modeling to assess the

impact of uncertainties in factors such as wind speed and electricity prices on the project's financial performance (Afanasyeva et al., 2016; Aquila et al., 2017)

**Control System Modeling:** Control system models simulate the operation of the turbine's control systems, including yaw control, pitch control, and generator control (Astolfi et al., 2019; Li et al., 2016; Song et al., 2018). These models are critical for optimizing the turbine's performance and ensuring safe operation under varying wind conditions (Astolfi et al., 2019). Control system models often incorporate feedback loops to adjust the turbine's operation based on real-time measurements of wind speed, rotor speed, and power output (Huerta et al., 2016; Pöschke et al., 2022).

## **2.6. Grid-Tie Hybrid Systems**

Grid-tie hybrid systems, also known as grid-connected HRES, are increasingly gaining attention as a viable solution to meet the growing energy demands while mitigating the environmental impact of traditional energy sources (Ahmed et al., 2024). As forementioned, these systems integrate multiple renewable energy sources, such as solar PV and wind energy, and connect them to the electrical grid. The combination of solar PV and wind energy in a grid-tie hybrid system takes advantage of the complementary nature of these resources, enhancing energy reliability, efficiency, and sustainability (Al-Najjar et al., 2022).

### **2.6.1. Integration of Solar PV and Wind Energy in Grid-Tie Hybrid Systems**

The integration of solar PV and wind energy in grid-tie hybrid systems is driven by the need to optimize renewable energy generation and reduce reliance on fossil fuels (Ahmed et al., 2024). Solar PV and wind energy are two of the most abundant and accessible renewable energy sources (Khare et al., 2016). Energy generation can be optimized to match varying load demands and environmental conditions, leading to a

more stable and reliable power supply by combining these technologies in a hybrid system (Chong et al., 2016; Dawoud et al., 2018).

As already mentioned, Solar PV and wind energy are complementary, therefore, they can compensate for each other's variability (Weschenfelder et al., 2020). Solar energy generation is typically highest during the day, especially in regions with high solar insolation, while wind energy generation often peaks at night or during periods of cloudy weather when solar output is low (Myers, 2017). This complementary behavior allows grid-tie hybrid systems to provide a more consistent power supply compared to standalone solar or wind systems (Twaha & Ramli, 2018). For instance, in a typical grid-tie hybrid system, during the daytime, solar PV panels generate electricity that can be used directly or fed into the grid. If the solar output exceeds the load demand, the excess energy can be stored in batteries or exported to the grid. At night, when solar generation is minimal or non-existent, wind turbines can take over as the primary source of energy. This dynamic integration ensures that the hybrid system can maintain power production even when one of the energy sources is not available, thereby reducing the overall dependency on the grid (Tazay et al., 2020).

A typical grid-tie hybrid system consists of several key components: solar PV panels, wind turbines, power inverters, energy storage systems (such as batteries), and grid-tie controllers (Xiao et al., 2018). The PV panels convert sunlight into DC electricity (Sampaio & González, 2017), while the wind turbines generate AC electricity from wind energy (Blaabjerg & Ma, 2017). Power inverters are used to convert DC electricity from the PV panels to AC, which is compatible with the grid and the load (Kavya Santhoshi et al., 2019). The energy storage system stores excess energy generated by the PV panels and wind turbines, which can be used later when generation is low (Rekioua, 2023). The grid-tie controller is crucial in managing the

flow of electricity between renewable energy sources, the energy storage system, and the grid (Tushar et al., 2016). It ensures that the power generated by the solar PV and wind turbines is efficiently utilized, either by supplying the load, charging the batteries, or exporting to the grid (Tushar et al., 2016). In case of excess generation, the controller also prevents the system from overloading the grid, thereby maintaining grid stability (Nascimento et al., 2021).

### **2.6.2. Advantages of Grid-Tie Hybrid Systems**

Grid-tie hybrid systems offer several advantages that make them an attractive option for both residential and commercial applications (Marais et al., 2018). These advantages include increased energy reliability, cost savings, environmental benefits, and grid stability (Al-Najjar et al., 2022).

#### **1. Increased Energy Reliability**

As already mentioned, one of the primary advantages of grid-tie hybrid systems is increased energy reliability (Yanine & Sauma, 2013). Hybrid systems can provide a continuous power supply, even in the face of fluctuating renewable energy generation by integrating solar PV and wind energy. The complementary nature of solar and wind resources means that when one resource is low, the other can often compensate, reducing the chances of power shortages (Weschenfelder et al., 2020). Hence, this complementary relationship reduces the need for backup generators and enhances the overall reliability of the power supply (Twaha & Ramli, 2018).

#### **2. Cost Savings**

Grid-tie hybrid systems can lead to significant cost savings over time (Yanine & Sauma, 2013). While the initial installation cost of a hybrid system may be higher

than a single-source renewable energy system, the long-term savings can be substantial (Sultan et al., 2018; Yanine & Sauma, 2013). Thus, grid-tie hybrid systems can reduce the reliance on grid electricity, leading to lower utility bills by generating electricity from renewable sources (Chand et al., 2019). Additionally, grid-tie hybrid systems can take advantage of net metering, where excess electricity generated by the system is exported to the grid, and the owner receives credits or payments from the utility company (Ostia et al., 2017). These financial incentives can further offset the costs of installing and maintaining the hybrid system (Saqib et al., 2021; Shabani & Chaaban, 2020)

### 3. Environmental Benefits

As already mentioned, the integration of solar PV and wind energy in grid-tie hybrid systems offers significant environmental benefits. By relying on renewable energy sources, these systems reduce greenhouse gas emissions and decrease the environmental impact of electricity generation (Amponsah et al., 2014). Unlike fossil fuel-based power plants, solar PV and wind turbines do not emit harmful pollutants or carbon dioxide (CO<sub>2</sub>) during operation, making them a clean and sustainable alternative (Üney & Çetinkaya, 2014). Moreover, grid-tie hybrid systems contribute to reducing the carbon footprint of energy production (Aeggegn et al., 2023). As countries and regions strive to meet their climate goals and transition to a low-carbon economy, the adoption of hybrid renewable energy systems can play a crucial role in achieving these objectives (Kabeyi & Olanrewaju, 2022).

### 4. Grid Stability and Resilience

Grid-tie hybrid systems enhance grid stability and resilience by providing distributed generation (Yanine et al., 2021). Distributed generation refers to the production of

electricity close to the point of use, which reduces the strain on centralized power plants and transmission infrastructure (Ali et al., 2020). Therefore, by generating electricity locally, grid-tie hybrid systems can help balance the load on the grid, especially during peak demand periods, and reduce the risk of blackouts or grid failures (Yanine et al., 2018, 2021). Additionally, the ability to store excess energy in batteries and feed it back into the grid when needed provides a buffer that can help stabilize the grid during periods of high demand or low renewable generation (Opiyo, 2016). This capability is particularly valuable in regions with high penetration of renewable energy, where variability in generation can pose challenges to grid operators (Opiyo, 2016; Ranaweera & Midtgård, 2016).

### **2.6.3. Challenges of Grid-Tie Hybrid Systems**

Despite their numerous advantages, grid-tie hybrid systems face several challenges that must be addressed to ensure their widespread adoption and optimal performance. These challenges include high initial costs, technical complexities, and grid integration issues (Yanine & Sauma, 2013).

#### **1. High Initial Costs**

The initial capital cost of installing a grid-tie hybrid system can be prohibitively high, especially when compared to traditional fossil fuel-based power generation or single-source renewable energy systems (Agajie et al., 2023). The cost of solar PV panels, wind turbines, inverters, and energy storage systems can add up quickly, making the investment challenging for some consumers (Ounnabi & Mounir, 2021; Rodriguez, 2014). Additionally, the cost of integrating these components into a cohesive and efficient system, along with the necessary infrastructure for grid connection, can further increase the overall expenses (Rodriguez, 2014). While the long-term savings

and environmental benefits are compelling, the high upfront cost remains a significant barrier to adoption, particularly in developing countries (Ahmed et al., 2022).

## 2. Technical Complexities

The integration of solar PV and wind energy into a grid-tie hybrid system requires sophisticated control systems (Yanine & Sauma, 2013) to manage the interaction between different energy sources, storage, and the grid. Ensuring that the system operates efficiently and reliably under varying environmental conditions and load demands is a complex task that requires advanced technology and expertise (Manandhar et al., 2017). Additionally, the variability and intermittency of renewable energy sources add another layer of complexity to the system design and operation (Mlilo et al., 2021). Moreover, balancing the power generation from solar PV and wind turbines, while maintaining grid stability and avoiding power quality issues, requires precise control and coordination (Tareen et al., 2017; Tavakoli et al., 2020).

## 3. Grid Integration Issues

Grid-tie hybrid systems must comply with the technical standards and regulations of the electrical grid they are connected to (Ahlstrom et al., 2021; Ardjoun et al., 2023). Integrating a hybrid system into the grid can be challenging, particularly in regions with less developed grid infrastructure or where grid standards are not well-defined (Ahlstrom et al., 2021; Tareen et al., 2017; Tavakoli et al., 2020). Additionally, the variability of renewable energy generation can pose challenges for grid operators in terms of balancing supply and demand (Jones, 2017; Martinot, 2016). Moreover, large-scale deployment of grid-tie hybrid systems requires careful planning and coordination with grid operators to ensure that the intermittent nature of renewable energy does not destabilize the grid (Oskouei et al., 2022).

#### 4. Energy Storage and Battery Management

While energy storage systems are a critical component of grid-tie hybrid systems, they also present challenges related to cost, performance, and management (Prakash et al., 2022). The cost of batteries, particularly large-scale lithium-ion batteries, remains high, contributing to the overall cost of the hybrid system (Chen et al., 2020). Additionally, the lifespan and efficiency of batteries can be affected by factors such as temperature, charging/discharging cycles, and the depth of discharge (Han et al., 2019). Furthermore, proper battery management is essential to maximize the lifespan and performance of the energy storage system, which can add complexity to the operation and maintenance of the hybrid system (Hannan et al., 2021).

#### **2.7. Stability in Power Systems**

Stability in power systems is a critical aspect of electrical engineering, ensuring that power systems can withstand disturbances and continue to operate effectively (Machowski et al., 2020). In the context of power systems, stability refers to the ability of the system to return to a state of equilibrium after being subjected to a disturbance, such as a fault or a sudden change in load (Machowski et al., 2020; Vittal et al., 2019). A stable power system maintains synchronous operation, ensuring that all generators operate at the same frequency and phase angle, allowing for a continuous and reliable supply of electricity (Meegahapola et al., 2020).

##### **2.7.1. Types of Stability**

Stability can be broadly categorized into two types: transient stability and steady-state stability (Shair, Li, et al., 2021). These two types of stability describe different aspects of how a power system responds to disturbances and how it returns to normal operation (Shair, Li, et al., 2021).

### **Transient Stability**

Transient stability refers to the power system's ability to maintain synchronism when subjected to severe and sudden disturbances, such as short circuits, line faults, or the sudden loss of a large generator or load (Khadka et al., 2020). Transient stability focuses on the system's dynamic behavior over a short period, typically ranging from milliseconds to a few seconds after the disturbance occurs (Hatziaargyriou et al., 2020). During a transient disturbance, the system experiences a rapid and significant change in the rotor angles of the generators (Zhou et al., 2016). If the power system can return to a state of equilibrium, where all generators remain in synchronism after the disturbance, it is considered to be transiently stable (Wu & Wang, 2020). However, if the disturbance causes the rotor angles to diverge significantly, leading to a loss of synchronism between generators, the system becomes unstable, potentially resulting in widespread blackouts or equipment damage (Wu & Wang, 2020). Transient stability is influenced by various factors, including the severity of the disturbance, the system's configuration, the inertia of the generators, and the speed of the protective relays and control systems (Sobbouhi & Vahedi, 2021). Thus, to enhance transient stability, power systems may employ techniques such as fast-acting circuit breakers, power system stabilizers, and automatic voltage regulators (Poulose & Kim, 2023).

### **Steady-State Stability**

Steady-state stability, on the other hand, refers to the power system's ability to maintain synchronism under small and gradual changes in operating conditions, such as gradual changes in load or generation (Khadka et al., 2020). Unlike transient stability, which deals with sudden disturbances, steady-state stability focuses on the system's behavior under normal operating conditions and how it responds to small perturbations (Khadka et al., 2020). Therefore, Steady-state stability is concerned with

the system's ability to maintain equilibrium over a longer period, typically minutes to hours, as it operates under varying loads and generation levels (Ledesma et al., 2017). A power system is considered to be steady-state stable if it can maintain synchronism and stable operation without significant oscillations or deviations in voltage and frequency (Remon et al., 2017). Steady-state stability is influenced by the system's configuration, the operating point, and the control strategies employed (Zhang et al., 2017). Studies have reported that systems with high levels of reactive power support and robust voltage control mechanisms tend to exhibit better steady-state stability (Liu et al., 2023). Additionally, to enhance steady-state stability, power systems may employ measures such as voltage regulators, capacitor banks, and reactive power compensation devices (Ismail et al., 2020; Siddique et al., 2019).

### **2.7.2. Importance of Stability Analysis in Hybrid Systems**

With the increased integration of renewable energy sources, such as solar PV and wind, into the power grid continues to grow, the stability of these hybrid systems becomes increasingly critical (Roy et al., 2022). HRES, which combines multiple energy sources, presents unique challenges and opportunities for stability analysis, particularly in the context of both transient and steady-state stability (Radovanovic, 2022).

#### **Integration Challenges in Hybrid Systems**

The integration of renewable energy sources into the power grid introduces several challenges related to stability. As forementioned, the primary challenge is the variability and intermittency of renewable energy sources (Sinsel et al., 2020). Solar PV and wind energy are both dependent on environmental conditions, such as sunlight and wind speed, which can fluctuate significantly over time. These fluctuations can

lead to sudden changes in power generation, potentially causing disturbances that affect the stability of the entire power system (Bessa et al., 2019; Sinsel et al., 2020).

In HRES, the combination of multiple energy sources, each with its dynamic characteristics, adds complexity to stability analysis (Roy et al., 2022). A study by Fernández-Guillamón et al. (2019), established that solar PV systems exhibit fast response times and low inertia, while wind turbines, particularly those with large rotor diameters, have higher inertia and slower response times. Therefore, the interaction between these different energy sources can lead to complex dynamic behavior that requires careful analysis to ensure stability (Fernández-Guillamón et al., 2019). Furthermore, the integration of energy storage systems, such as batteries, into HRES introduces additional stability considerations (Hannan et al., 2021). Energy storage can help mitigate the effects of variability by storing excess energy and releasing it during periods of low generation, it also introduces new dynamics into the system (Hannan et al., 2021). Additionally, the charging and discharging cycles of batteries can affect the system's overall stability, particularly during transient events (Datta et al., 2021).

### **Transient Stability Analysis in Hybrid Systems**

Transient stability analysis is particularly important in HRES due to the potential for large and sudden disturbances (Saleem et al., 2024). In a hybrid system, the sudden loss of a renewable energy source, such as a wind turbine tripping offline due to a fault, can cause significant changes in power flow and rotor angles (Jaen-Cuellar et al., 2022). If the faults are not properly managed, these changes can lead to a loss of synchronism and potential system collapse (Jaen-Cuellar et al., 2022; Shair et al., 2019). To address these challenges, transient stability analysis in HRES involves simulating various disturbance scenarios and evaluating the system's response

(Radovanović & Milanović, 2021). This analysis helps identify potential vulnerabilities and enables the design of control strategies and protective measures to enhance stability (Radovanović & Milanović, 2021). A study by Radovanović & Milanović (2023) applied Deep Learning-Based Equivalent Modelling of a Hybrid system for Efficient, Repetitive Power System Transient Stability. Additionally, a review by Sahu et al. (2020) presented the use of fast-acting circuit breakers, dynamic reactive power compensation, and advanced control algorithms can help improve transient stability in hybrid systems. Furthermore, transient stability analysis is essential for ensuring the reliable operation of microgrids, which are often powered by HRES (Adefarati & Bansal, 2019). Microgrids are designed to operate independently or in conjunction with the main grid, and their stability is crucial for providing a consistent power supply to local loads (Khare & Chaturvedi, 2023). Therefore, transient stability analysis helps ensure that microgrids can quickly recover from disturbances and maintain operation without disconnecting from the main grid or causing local blackouts (Bihari et al., 2021).

### **Steady-State Stability Analysis in Hybrid Systems**

Steady-state stability analysis is equally important in HRES, particularly in the context of long-term operation under varying load and generation conditions (Radovanovic, 2022; Rehman et al., 2020). As HRES operate over extended periods, they must maintain synchronism and stable voltage and frequency levels despite gradual changes in load and generation (Rehman et al., 2020). In hybrid systems, the interaction between different energy sources can lead to complex voltage and frequency dynamics (Malik et al., 2017). Anvari et al. (2016) expressed that a sudden drop in solar irradiance may reduce the output of a solar PV system, leading to a corresponding increase in the load on the wind turbines. Hence, if the system is not

properly balanced, these changes can cause voltage and frequency deviations that affect steady-state stability (Ssekulima et al., 2016). As already mentioned, Steady-state stability analysis in HRES involves evaluating the system's response to small perturbations and ensuring that it can maintain stable operation without significant oscillations (Radovanovic, 2022). Similarly, this analysis is particularly important for optimizing the operation of hybrid systems and ensuring that they can meet load demands while maintaining stability (Roy et al., 2022).

Additionally, steady-state stability analysis is critical for the integration of HRES into the main power grid (Krishan & Suhag, 2020). As the penetration of renewable energy increases, the grid must be able to accommodate the dynamic behavior of hybrid systems without compromising overall stability (Mohandes et al., 2019). Steady-state stability analysis helps identify the optimal operating conditions and control strategies for integrating HRES into the grid, ensuring that they contribute to grid stability rather than causing disruptions (Pavankumar, 2023).

## **2.8. Research and Knowledge Gaps**

HRES has garnered significant attention in recent years due to its potential to enhance the reliability and sustainability of power generation by integrating multiple renewable energy sources, such as solar PV and wind (Khan et al., 2022; Mohammed et al., 2014). However, the stability of these systems, particularly in grid-tied configurations, poses challenges that require comprehensive analysis (Roy et al., 2022). This section reviews the existing literature on the stability analysis of HRES, focusing on both transient and steady-state stability. Additionally, it identifies gaps in the current research that warrant further investigation.

As forementioned, stability analysis in power systems is crucial for ensuring a reliable and continuous power supply (Hatziaargyriou et al., 2020). Additionally, in the context of HRES, stability issues arise due to the inherent variability of renewable energy sources and the complex interactions between different system components (Hossain et al., 2018). The literature on stability analysis of HRES is extensive, covering various aspects such as modeling, control strategies, and simulation techniques (Hosseinalizadeh et al., 2016; Khan et al., 2022; Khan et al., 2022).

### **2.8.1. Transient Stability Analysis of Hybrid Systems**

One of the early studies on transient stability in HRES was conducted by Bossanyi (2003), who explored the impact of wind power integration on the transient stability of power systems. The study highlighted that the intermittent nature of wind energy could exacerbate stability issues, particularly during severe disturbances. The authors proposed control strategies to mitigate these effects, such as the use of dynamic braking and pitch control of wind turbines. Yan & Wang (2017) focused on additional damping control strategies for wind turbine small-signal stability. Similarly, Ou et al. (2017) introduced a novel intelligent damping controller consisting of a proportional–integral–derivative (PID) linear controller. The proposed technique effectively stabilized the network under unstable conditions.

Another significant contribution was made by Xu et al. (2019), who developed a comprehensive model for analyzing the transient stability of a hybrid system comprising wind, solar PV, and conventional generators. The study employed time-domain simulations to assess the system's response to various disturbances. The findings indicated that the integration of renewable energy sources could improve the system's transient stability, provided that appropriate control mechanisms were in place. Movahedi et al. (2019) designed static synchronous series compensator (SSSC),

thyristor-controlled series compensator (TCSC), and static synchronous compensator (STATCOM) controllers using adaptive velocity update relaxation particle swarm optimization (AVURPSO) algorithm, gravitational search algorithm (GSA), and genetic algorithm (GA) for transient stability improvement of a multi-machine power system with PV and wind farms. Alsakati et al. (2021) reported on a transient stability assessment of the IEEE 9-Bus system integrated wind power system and reported that high penetration of wind energy has a destabilizing impact on the power system however, the location of the wind farm affects transient stability.

More recent studies have focused on advanced control strategies to enhance the transient stability of HRES. For instance, Maaruf et al. (2022) proposed a robust sliding mode control strategy for both standalone and grid-connected operation of Solar-Wind-Battery HRES. The study reported a significantly improved robustness and better power management in terms of overshoot and settling time with enhanced tracking capability towards the calculated optimal operation of the HRES under different external generation or load disturbances and internal parameter uncertainties. Additionally, Reza et al. (2023) and Venkatesan et al., (2024) investigated the use of coordinated control of battery energy storage systems (BESS) and flexible AC transmission systems (FACTS) devices in improving the transient stability of grid-tied HRES. The studies demonstrated that the coordinated control approach could effectively dampen oscillations and maintain synchronism during disturbances.

### **2.8.2. Steady-State Stability Analysis of Hybrid Systems**

In HRES, steady-state stability is influenced by the variability of renewable energy sources and the interaction between different system components (Krishan & Suhag, 2020). One of the foundational studies on steady-state stability in HRES was conducted by Verdejo et al. (2016), who examined the impact of large-scale wind

power integration on steady-state stability based on Lyapunov exponent to determine the impact of wind power penetration level on the operation of a power system. Similarly, Aththanayake et al. (2020), employed eigenvalue analysis to assess the system's stability margins and identified potential issues related to voltage stability and reactive power management. The author suggested the use of reactive power compensation and voltage control techniques to enhance stability. Sharif et al. (2017) expanded on this work by analyzing the steady-state stability of a hybrid system integrating wind, solar PV, and diesel generators. The study utilized a small-signal stability analysis to evaluate the system's response to gradual changes in load and generation. The results indicated that the hybrid system could maintain steady-state stability under normal operating conditions but might experience instability under certain scenarios, such as high penetration of renewable energy and low inertia.

Recent research has focused on the integration of advanced technologies to improve steady-state stability in HRES. Yao et al. (2019), proposed a multiperiod optimal power-flow technique that applies demand-responsive loads to improve the steady-state voltage stability. The study reported that demand response (DR) actions can improve static voltage stability more cost-effectively than generation actions on the IEEE 118-bus system. Similarly, Misaghian et al. (2022) explored the use of DR strategies in enhancing the steady-state stability of hybrid systems. The study employed a detailed power flow analysis and demonstrated that DR could significantly improve voltage stability and reduce the likelihood of voltage collapse.

### **2.8.3. Combined Stability Analysis**

Some studies have taken a holistic approach by analyzing both transient and steady-state stability in HRES. Research by Bhukya & Singh (2024) proposed a coordinated control technique for generators, wind farms, and energy storage on the IEEE 9-bus

test system based on Real Time Digital Simulator (RTDS) simulations the system successfully mitigated uncertainties and fortified system stability across diverse conditions. Chankaya et al. (2022) developed a comprehensive stability assessment framework for a grid-tied hybrid system combining solar PV, wind, and energy storage. The study employed chaotic grey-wolf optimization to evaluate the system's stability under various scenarios. The results indicated that while energy storage systems could enhance both transient and steady-state stability, careful coordination of control strategies was necessary to avoid adverse interactions between different components. Similarly, Abbassi et al. (2022) developed a Moth-Flame optimization algorithm to improve the stability of off-grid PV-wind HRES. Rasool et al. (2023) proposed a multi-objective optimization approach for improving the stability of HRES. The study integrated transient and steady-state stability criteria into the optimization framework and employed evolutionary algorithms to identify optimal control settings. The findings demonstrated that the proposed approach could enhance overall system stability while minimizing operational costs. Additionally, Pavankumar et al. (2021) introduced a Multi-objective optimization of PV-wind-biomass-battery-based grid-integrated HRES. The study considered the time-varying nature of the RES and reported that by including HRES, the system becomes more reliable and the unit cost of energy with the optimized sizing configuration is much lesser than the unit cost of energy purchased from the grid.

#### **2.8.4. Knowledge Gaps in the Existing Literature**

While the existing literature on the stability analysis of HRES provides valuable insights, several gaps remain that warrant further investigation. A summary of these research gaps is given in Table 2.1.

## **1. Limited Focus on Emerging Renewable Energy Technologies**

Most of the current research focuses on traditional renewable energy sources, such as solar PV and wind. However, emerging technologies, such as tidal, wave, and geothermal energy, are gaining traction and are being integrated into hybrid systems. There is a need for more studies that explore the stability implications of these emerging technologies, particularly when combined with solar PV and wind in HRES.

## **2. Lack of Real-Time Stability Analysis**

Much of the existing research relies on offline simulations and theoretical models to assess stability. While these approaches provide valuable insights, they may not fully capture the dynamic behavior of HRES in real-world conditions. There is a growing need for real-time stability analysis methods that can monitor and assess the stability of HRES in real time, enabling proactive management and control of the system.

## **3. Integration of Advanced Control Strategies**

While some studies have explored advanced control strategies, such as coordinated control of BESS and FACTS devices, there is still a lack of comprehensive research on the integration of these strategies into HRES. Specifically, there is a need for more studies that explore the potential of machine learning (ML) and artificial intelligence (AI) techniques in enhancing the stability of hybrid systems. These techniques could enable more adaptive and intelligent control strategies that respond to changing conditions in real time.

## **4. Interactions Between Different Stability Modes**

The existing literature often treats transient and steady-state stability as separate issues, with limited exploration of the interactions between these stability modes.

However, in practice, disturbances in one stability mode can affect the other, leading to complex interactions that may not be fully captured by traditional analysis methods. There is a need for more research that explores these interactions and develops integrated stability assessment frameworks that consider both transient and steady-state stability.

## **5. Impact of High Renewable Penetration**

As the penetration of renewable energy in power systems continues to increase, the stability challenges associated with HRES are likely to become more pronounced. While some studies have explored the impact of high renewable penetration on stability, there is still a lack of comprehensive research that considers the full range of scenarios and operating conditions that may arise in future power systems. This includes the potential impact of grid code changes, market regulations, and new technologies on the stability of HRES.

## **6. Socio-Economic and Environmental Considerations**

Most of the existing research on the stability analysis of HRES focuses on technical aspects, with limited consideration of socio-economic and environmental factors. However, these factors play a crucial role in the adoption and operation of HRES. For example, the cost of stability-enhancing technologies, the availability of resources, and the environmental impact of system components can all influence the feasibility and sustainability of HRES. There is a need for more interdisciplinary research that integrates technical, socio-economic, and environmental considerations into stability analysis.

## **2.9. Theoretical Framework**

Generally, solar PV systems are a cornerstone of modern renewable energy technology, offering a sustainable and increasingly cost-effective solution for electricity generation. As the technology continues to advance and costs decrease, solar PV systems are expected to play an even more significant role in the global energy transition, contributing to the reduction of greenhouse gas emissions and the achievement of energy security. Additionally, wind energy systems are a vital component of the global transition to renewable energy, offering a sustainable and reliable source of electricity. The basic principles and components of wind turbines, including the rotor, nacelle, generator, tower, and control systems, work together to convert wind energy into electrical energy. The performance characteristics of wind energy systems, such as wind speed, capacity factor, and aerodynamic efficiency, are critical for optimizing energy production and ensuring the reliability of the turbine. Accurate modeling of wind energy systems, including aerodynamic, structural dynamics, energy yield, economic, and control system models, is essential for optimizing turbine performance, predicting energy output, and assessing the economic viability of wind energy projects. As technology continues to advance, wind energy systems are poised to play an increasingly important role in the global energy mix, contributing to a more sustainable and resilient energy future. Furthermore, Grid-tie hybrid systems that integrate solar PV and wind energy offer a promising solution to the challenges of energy generation in a world increasingly focused on sustainability and resilience. These systems provide numerous advantages, including increased energy reliability, cost savings, environmental benefits, and enhanced grid stability. However, they also face challenges such as high initial costs, technical complexities, and grid integration issues that must be addressed to fully realize their

potential. As technology advances and the cost of renewable energy continues to decline, grid-tie hybrid systems are likely to play an increasingly important role in the global energy landscape. Moreover, stability in power systems, encompassing both transient and steady-state stability, is a fundamental aspect of ensuring the reliable and continuous operation of electrical grids. In the context of hybrid renewable energy systems, stability analysis is crucial for addressing the unique challenges posed by the integration of multiple renewable energy sources.

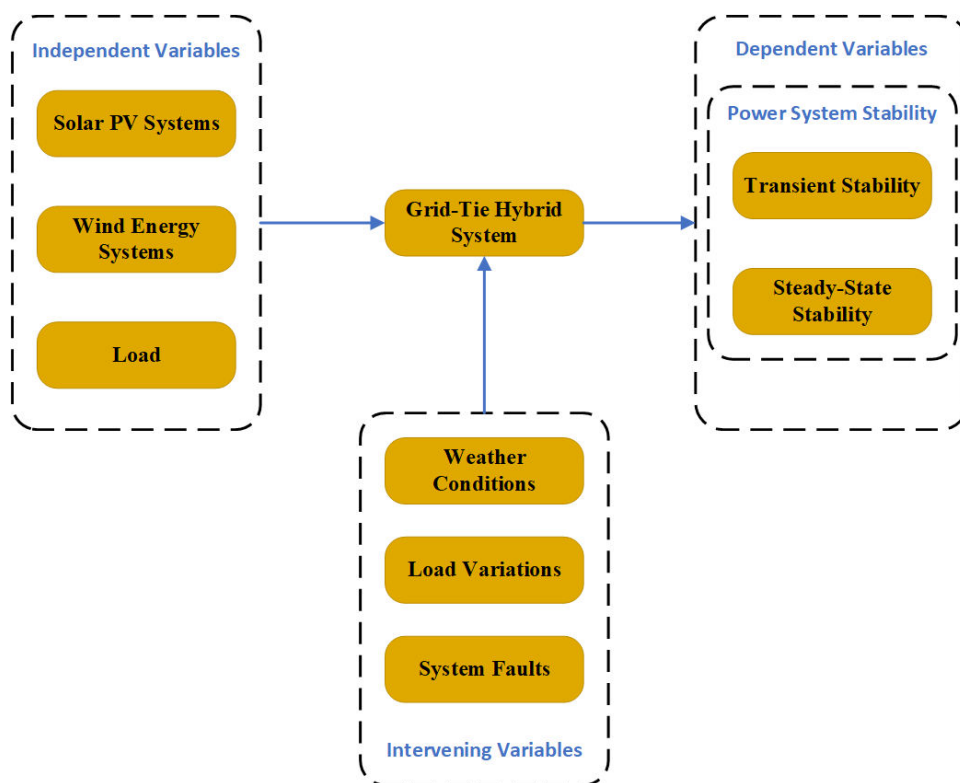


Figure 2.6: The conceptual frame of the study

As the adoption of HRES continues to grow, the importance of stability analysis will only increase, ensuring that these systems can operate effectively and contribute to a sustainable energy future. Lastly, the stability analysis of hybrid renewable energy systems is a critical area of research that has seen significant advancements in recent years. The existing literature provides valuable insights into the challenges and opportunities associated with ensuring the stability of these systems, particularly in

the context of grid integration. However, several gaps remain that warrant further investigation, including the need for real-time stability analysis, the integration of advanced control strategies, and the exploration of interactions between different stability modes. Addressing these gaps will be crucial for the continued development and deployment of HRES as a sustainable and reliable solution for meeting global energy needs. The conceptual framework of this introduced study is given in Figure 2.6.

Table 2.1: Summary of knowledge gaps

Thematic area	Brief Description	Methodology Used	Results	Research Gap	Reference
Transient Stability Analysis	Analysis of the impact of disturbances (e.g., faults) on the synchronism of HRES components	Time-domain simulations, control strategy design	Identified control strategies to mitigate transient instability in HRES	Limited exploration of real-time stability analysis and the impact of emerging renewable energy technologies	(Nnoli et al., 2023)
Steady-State Stability	Assessment of the ability of HRES to maintain a stable operating point under small disturbances	Eigenvalue analysis, small-signal stability analysis	Identified potential voltage stability issues and the need for reactive power management	Need for more research on the integration of emerging renewable technologies and demand response strategies	(Radovanović & Milanović, 2021)
Combined Stability	Holistic approach to analyzing both transient and steady-state stability in HRES	Time-domain simulations, eigenvalue analysis	Showed that energy storage systems can enhance both types of stability, but require careful control coordination	Insufficient studies on the interactions between transient and steady-state stability modes and their combined impacts	(Bhukya & Singh, 2024)
Advanced Control Strategies	Use of advanced control strategies, such as coordinated control of BESS and FACTS devices, in HRES	Coordinated control, optimization techniques	Demonstrated the potential of advanced control strategies to enhance HRES stability	Lack of research on the integration of AI and ML in control strategies and their real-time implementation in HRES	(Chankaya et al., 2022)
High Renewable Penetration	Impact of high penetration levels of	Power flow analysis, stability assessment frameworks	Indicated potential stability challenges under high renewable	Need for comprehensive studies considering future scenarios with very high	(Verdejo et al., 2016)

	renewable energy on HRES stability		energy penetration scenarios	renewable energy penetration	
Socio-Economic and Environmental Factors	Consideration of socio-economic and environmental factors in the stability analysis of HRES	Interdisciplinary analysis, cost-benefit analysis	Limited focus on socio-economic and environmental impacts of stability-enhancing technologies	Need for more interdisciplinary research that integrates technical, socio-economic, and environmental considerations in stability analysis	(N. Kumar et al., 2023)

# CHAPTER THREE

## MATERIALS AND METHODS

### 3.1. Introduction

In this chapter, a comprehensive overview of the experimental methods, techniques, and simulation tools employed in this research endeavor to accomplish the defined objectives is provided. Figure 3.1 below illustrates the research layout of the methodology used in the study to achieve the objectives.

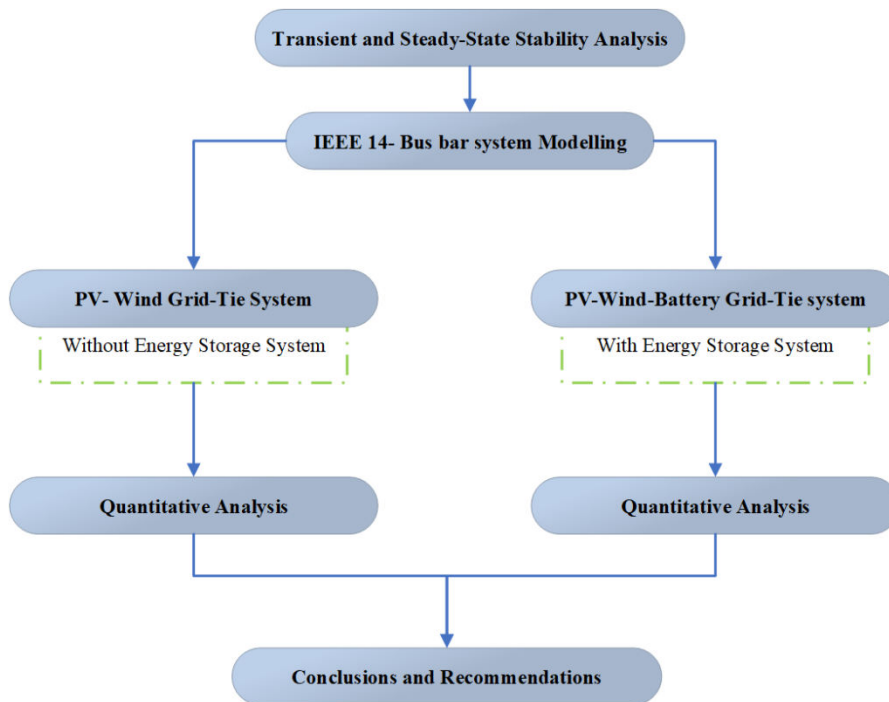


Figure 3.1: The research logic flow based on objectives

### 3.2. Research Design

The research design for this study on the transient and steady-state stability analysis of a solar PV-wind grid-tie hybrid system is structured to provide a comprehensive understanding of the stability challenges and potential solutions associated with integrating these renewable energy sources into the grid. The research design flow is given in Figure 3.2. The overall approach is rooted in a combination of system

modeling, simulation, and analytical techniques, which are essential for examining both the transient and steady-state behavior of hybrid renewable energy systems.

This study employs a quantitative research approach, leveraging mathematical modeling and computer-based simulations to analyze the stability of a solar PV-wind grid-tie hybrid system. The quantitative approach is appropriate because it allows for precise, objective measurements and the application of statistical and computational tools to assess the system's performance under various conditions (Jagacinski & Flach, 2018). This study modeled the dynamic interactions between the solar PV system, wind turbine, and the power grid by using Electrical Transient Analyzer Program (ETAP®) simulation software. This model was used to simulate various scenarios, including changes in weather conditions (gradual variations in solar irradiance and wind speed), and grid disturbances (faults).

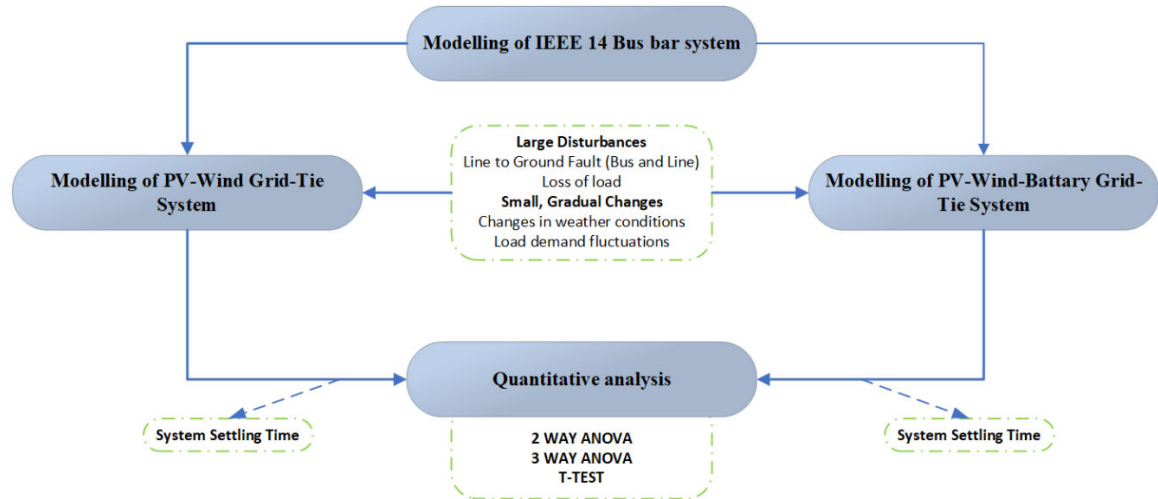


Figure 3.2: The research design flow

Based on the objectives, this study provided a holistic approach to HRES stability analysis with a comparative analysis of HRES with and without battery energy storage system (BESS) based on transient stability analysis and steady-state stability analysis. Transient stability focused on the system's ability to maintain synchronism when

subjected to large disturbances, thus, a Line-to-ground (LG) fault was applied. The choice for LG was because it's the most common type of system fault in power systems (Datta et al., 2020). Steady-state stability, on the other hand, examines the system's ability to return to normal operation after small, gradual changes in load or generation (Hatziaargyriou et al., 2020). In this research, Steady-state stability was examined based on gradual variations in solar irradiance and wind speed (Hatziaargyriou et al., 2020). Therefore, by addressing both types of stability, the research aims to provide a holistic assessment of the hybrid system's reliability.

The choice of a quantitative, simulation-based methodology is justified by the need for precision and the complexity of the systems being studied. HRES involves numerous variables, including fluctuating energy inputs from solar and wind sources, dynamic interactions with the power grid, and the need for sophisticated control mechanisms to maintain stability (Babatunde et al., 2020). ETAP<sup>®</sup> Simulation tool is particularly well-suited to handling this complexity, as it allows for the modeling of intricate systems with multiple interacting components and the analysis of their behavior under a wide range of conditions (Shair, Xie, et al., 2021). Additionally, this methodology enables the study to investigate the effects of specific variables, such as changes in solar irradiance ( $I_r$ ), wind speed ( $S_w$ ), fault clearance time ( $t_{ct}$ ), and fault position on a Transmission line ( $F_p$ ), on the overall stability of the HRES based on the setting time ( $t_s$ ). By systematically varying these inputs in the simulations, the research can identify critical thresholds and potential weaknesses in the system design, providing valuable insights for improving stability. Furthermore, the use of simulation-based analysis also allows for the replication of real-world conditions without the need for physical prototypes, which can be costly and time-consuming to develop (Łukaszewicz, 2019). This is particularly important in the context of

renewable energy systems, where the integration of new technologies must be thoroughly tested before deployment to ensure grid reliability and prevent power outages (Chen et al., 2017). The ability to conduct extensive testing in a virtual environment makes simulation an efficient and effective tool for stability analysis. Moreover, the quantitative approach provides a solid foundation for the application of control strategies designed to enhance system stability. Therefore by analyzing the simulation results, the study can propose specific control techniques, such as the application and sizing of BESS MPPT for solar PV or pitch control for wind turbines, which are tailored to the unique characteristics of the HRES (Khare et al., 2016)

### **3.3. Electrical Transient Analyzer Program (ETAP®) System**

#### **Modeling**

The ETAP is a highly regarded commercial software developed in 1983, designed for comprehensive analysis and simulation of electrical power systems (Liu, 2019). ETAP offers a wide array of over 50 integrated modules, including power flow analysis, short-circuit analysis, motor starting, and transient stability (Shertukde, 2019). These modules provide users with versatile tools to address various stages of power system planning, design, analysis, and real-time operational control (Shertukde, 2019). The software is particularly noted for its user-friendly interface, which allows engineers to simulate and model complex electrical networks, including power generation, transmission, distribution, microgrids, and industrial systems, with ease (Liu, 2019; Shertukde, 2019). ETAP's intuitive drag-and-drop functionality simplifies the creation of detailed simulations, making it accessible to both novice and experienced users (Liu, 2019; Shertukde, 2019). Moreover, ETAP's powerful data visualization and reporting features ensure that all aspects of the electrical network are accurately represented and easily interpretable (Liu, 2019; Shertukde, 2019). This

enables users to not only perform rigorous theoretical analyses but also to validate these findings through detailed simulation results, enhancing the reliability and scientific rigor of their work (Liu, 2019; Shertukde, 2019). Therefore, ETAP stands as a critical tool in the field of electrical engineering, supporting both academic research and practical applications.

Table 3.1: The Simulated IEEE 14-bus system data

<b>Generators</b>				
<b>Generator</b>	<b>MW</b>	<b>kV</b>	<b>PF</b>	<b>MVA</b>
Gen_1-2	250	132	98	255.102
Gen_2-3	450	132	99	454.545
Gen_3-2	100	132	96	104.167
Gen_8-2	250	11	98	255.102
Gen_6-3	450	33	99	454.545
<b>Lamped loads</b>				
<b>Loads</b>	<b>MVA</b>	<b>MW</b>	<b>Mvar</b>	<b>PF</b>
Load_1-2	50	45	21.794	90
Load_2-2	50	45.945	19.725	91.9
Load_3-2	25	24.25	6.078	97
Load_7-2	10	9.2	3.919	92
Load_4-2	40	37.6	13.647	94
Load_5-2	100	94	34.117	94
Load_6-2	100	95	31.225	95
Load_7-2	10	9.2	3.919	92
Load_10-2	10	9.7	2.431	97
Load_9-2	25	24	7	96
Load_12-2	5	4.75	1.561	95
Load_11-2	5	4.75	1.561	95
Load_14-22	2	1.7	1.054	85
Load_13-2	10	9.2	3.919	92
<b>Transmission Lines</b>				
Configuration	Type	Horizontal		
	Height	15 m		
	Spacing per phase	2 m		
Parameters	Conductor	T&D Book, Quail 2/0		
	Ground wire	EPRI 3 No 10		
	Impedance per phase	Calculated		
<b>Transformers</b>				
<b>Transformer</b>	<b>Primary</b>	<b>Secondary</b>	<b>MVA</b>	<b>Impedance</b>
	kV	kV		
T 5_6-2	33	132	240	Typical Z & X/R
T 4_9-2	33	132	240	Typical Z & X/R
T 4_7-2	11	132	200	Typical Z & X/R
T 4_9-4	33	11	110	Typical Z & X/R

### 3.3.1. Simulation of IEEE 14BUS System

The simulation of the IEEE 14-bus system using ETAP provided an in-depth analysis of power flow and stability within a standard test case for electrical power systems. The IEEE 14-bus system, a simplified model representing a portion of the American Electric Power (AEP) system (Midwestern U.S.), is widely used in academic and industry research for validating algorithms and methodologies in power system analysis (Do Coutto Filho et al., 2022). The IEEE 14-bus system was modeled to include 14 buses, 5 generators, 14 loads, 17 transmission lines, and 4 transformers (Reddy et al., 2016). The data used in modeling the IEEE 14-bus system is given in Table 3.1.

Table 3.2: The Simulated Solar PV-Wind grid tied System data

<b>Wind Turbine</b>					
<b>Wind turbine</b>	<b>MW</b>	<b>kV</b>	<b>PF</b>		
WTG2_13-2	20	0.575	95		
WTG2_10-2	20	0.575	95		
<b>Solar PVs</b>					
<b>Solar PV</b>	<b>Cells</b>	<b>V(DC)</b>	<b>Panels</b>	<b>kW (DC)</b>	
PV A3_3-2	60	1000	400	91.71	
PV A1_14-2	60	1000	500	113.1	
<b>Inverters</b>					
<b>Inverter</b>	<b>kW (DC)</b>	<b>V (DC)</b>	<b>KVA (AC)</b>	<b>kV (AC)</b>	
Inv1	166.7	33	150	33	
Inv2	200	33	180	33	
<b>Batteries</b>					
<b>Battery</b>	<b>Strings</b>	<b>Plates</b>	<b>Cells</b>	<b>Capacity (AH)</b>	
Battery_1	1	37	250	1350	
Battery_2	1	37	250	1350	
<b>Charger inverter</b>					
	<b>kVA (AC)</b>	<b>KV (AC)</b>	<b>PF</b>	<b>KW (DC)</b>	<b>V (DC)</b>
Charger_1	5	33	85	3.83	600
Charger_2	5	33	85	3.83	600
Inv_1	225	33	99	250	600
Inv_2	135	33	99	150	600

The simulation process began with the drawing of the one-line diagram of the system, after which power flow analysis was performed, i.e., Load Flow Analysis based on the Newton-Raphson method, which calculates the voltage magnitudes and angles at

each bus, as well as the power flowing through the transmission lines. This analysis helped to identify areas of potential voltage instability, power losses, and bottlenecks in the system before the addition of PV and Wind power resources (stable buses far from the generators, Solar PV, Wind, and BESS resources were added). The parameters of the Solar PV, Wind, and BESS resources are presented in Table 3.2. Several studies have been performed on the stability analysis of the IEEE 14-bus system, therefore, this study will only focus on the stability analysis of the Solar PV-Wind grid-tied System with a comparative analysis of with and without BESS.

### **3.4. Data collection**

#### **3.4.1. Transient Stability Simulation**

The ETAP simulation facilitates the transient stability of the HRES grid-tie system. Two plausible grid disturbances were explored, i.e., faults on buses and faults on the transmission line at different  $F_p$  (0%, 10%, 25%, 50%, 75%, 90%, and 100%) with a  $t_{ct}$  of 1.05 s, 1.5 s, and 2.0 s, and the faults occurring at 1.0 s. The transient stability analysis in ETAP assesses the system's response to these disturbances through the analysis of the  $t_s$ . This is a time-domain simulation that involves solving the differential-algebraic equations (DAEs) that govern the system's dynamics over a short period, typically ranging from a few milliseconds to several seconds. The key variables of interest are the  $t_s$  of such generator speed ( $G_s$ ), voltages ( $V$ ), and frequency ( $f$ ). Transient stability data was collected through the following steps. Firstly, LG fault was simulated on each bus and the  $t_s$  for  $G_s$  (for all generators),  $V$  (for all buses), and  $f$  (for all buses) were collected for each  $t_{ct}$ . Secondly, LG fault was simulated on each transmission line at different  $F_p$ , for each  $F_p$  the  $t_s$  for  $G_s$  (for all generators),  $V$  (for all buses), and  $f$  (for all buses) were collected for each  $t_{ct}$ .

Thirdly, load loss at each lumped load was simulated, and the  $t_s$  for  $G_s$  (for all generators),  $V$  (for all buses), and  $f$  (for all buses) were collected for each  $t_{ct}$ . The  $t_s$  were then analyzed to assess the system's transient stability. Key indicators include the stability margin, which measures the system's ability to return to a stable state after the disturbance, and the damping of oscillations, which indicates how quickly the system's oscillations decay over time. Note that the simulation time was set to 50 Seconds for the entire study.

Table 3.3: Summary of collected data

Transient Stability ( $t_s$ )			Steady-State Stability ( $t_s$ )	
Fault on Bus	Fault on Line	Loss of Load	Varying $I_r$	Varying $S_w$
588	4998	462	588	588

Lastly, the role of the energy storage system in enhancing transient stability was analyzed. The storage system can provide immediate power support during disturbances, helping to stabilize the system. All the  $t_s$  was collected via the Excel data export option in ETAP and saved in the internal storage of Microsoft Windows 11 PC (intel core i5-iRISXe CPU, 4 GHz, 16 GB (Intel, Santa Clara, CA, USA)). A summary of the collected data is given in Table 3.3.

### 3.4.2. Steady-State Stability Simulation

Power flow analysis was applied to determine the steady-state operating conditions of the system, including the voltage levels, power flows, and losses across the network. This analysis was performed using ETAP software capable of solving the nonlinear algebraic equations that represent the power flow in the system. Similarly in the steady-state stability analysis,  $t_s$  was applied regarding gradually varying  $I_r$ , and  $S_w$ .

### Eigenvalue Analysis

Eigenvalue analysis is a key tool for assessing the dynamic stability of the power system under steady-state conditions. The eigenvalues of the system's state matrix

were calculated to determine the stability margins and identify any potential oscillatory modes. The system state matrix was calculated using a Single Machine Infinite Bus (SMIB) system which is commonly used for stability analysis (Du et al., 2020) based on Eq. 3.1

$$\begin{aligned}\dot{\delta} &= \omega_0(\omega - 1) \\ M\dot{\omega} &= P_m - P_e - D(\omega - 1)\end{aligned}\quad (3.1)$$

Where,  $\delta$  is the rotor angle of the generator,  $\omega$  is the rotor speed deviation from synchronous speed,  $P_m$  is the mechanical input power to the generator,  $P_e$  is the electrical output power of the generator,  $M$  is the inertia constant of the generator,  $D$  is the damping coefficient, and  $\omega_0$  is the synchronous speed of the generator. Linearization of the system was performed around the operating point. A small perturbation  $\Delta\delta$  and  $\Delta\omega$  around the steady-state operating point ( $\delta_0, \omega_0 = 1$ ) was assumed to give a linearized Eq. 3.2.

$$\begin{aligned}\Delta\dot{\delta} &= \omega_0\Delta\omega \\ M\Delta\dot{\omega} &= \Delta P_m - \Delta P_e - D\Delta\omega\end{aligned}\quad (3.2)$$

$P_e$  was approximated as  $P_e = P_0 + K_\delta\Delta\delta$ , where  $K_\delta$  is the sensitivity of electrical power to the rotor angle, therefore the State-Space Representation of the system is given by Eq. 3.3.

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 \\ -\frac{K_\delta}{M} & -\frac{D}{M} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{M} \end{bmatrix} \Delta P_m \quad (3.3)$$

### 3.5. Statistical analysis

This study aimed to analyze stability based on  $t_s$  for Solar PV-Wind HRES and Solar PV-Wind-Battery HRES and provide a comparative analysis. All statistical computations were performed using SPSS software package version 25.0 (SPSS Inc., Chicago, IL, USA). Before the statistical analysis, the data was tested for normality

using the Shapiro-Wilk Test of Normality (González-Estrada et al., 2022) to guide the choice for parametric or non-parametric analysis as well as data transformation to achieve normality. This study was divided into two sections, firstly, for a Grid-Tied Solar PV-Wind HRES the aim was to examine the effect of  $t_{ct}$ , and  $F_p$  on the  $t_s$ , therefore 2-way ANOVA (Somerfield et al., 2021a) was applied. Secondly, 3-way ANOVA (Somerfield et al., 2021b) was applied to determine the effect of  $t_{ct}$ ,  $F_p$  and Battery on the  $t_s$  of a Grid-Tied Solar PV-Wind-Battery HRES. Additionally, a T-test (De Winter, 2019) was performed to establish if there was a statistically significant difference between  $t_s$  of a Grid-Tied Solar PV-Wind HRES and  $t_s$  of a Grid-Tied Solar PV-Wind-Battery HRES.

### **3.6. Conclusion**

The chosen research design, with its emphasis on quantitative analysis and simulation, is well-suited to the objectives of this study. It allows for a detailed and accurate assessment of the stability of solar PV-wind grid-tie hybrid systems, providing insights that are critical for the successful integration of renewable energy into the power grid. Additionally, the detailed modeling of the hybrid solar PV-wind system integrates the individual component models into a cohesive system. While the model includes necessary assumptions and simplifications to focus on key stability aspects, it provides a robust foundation for analyzing the transient and steady-state behavior of the hybrid system under different operating conditions.

## CHAPTER FOUR

### RESULTS AND DISCUSSIONS

#### 4.1. Introduction

This section presents the results and the research findings of this study. The results depicted in this chapter demonstrate the stability of the HRES system and the methodology proposed in the previous chapters.

#### 4.2. IEEE 14BUS System

The IEEE 14-bus system is a well-known test case that represents a simplified model of an electric power system, making it ideal for conducting stability and load flow studies (Veerasley et al., 2021). The simulation of the IEEE 14-bus system using ETAP software provided valuable insights into the operational performance and stability characteristics of a typical power system network under various scenarios. The simulated IEEE 14-bus system is given in Figure 4.1.

The load flow analysis was conducted to determine the steady-state operating conditions of the IEEE 14-bus system. The simulation results revealed the voltage levels at each bus, the power flows along transmission lines, and the power losses in the network. The results indicated that the system operated within acceptable voltage limits, with bus voltages ranging between 0.98 p.u. and 1.00 p.u. The power losses were minimal, highlighting the efficiency of the network under normal operating conditions. The bus with the lowest bus voltages was Bus 10 (0.9832 p.u.) while Bus 1, 2, and 3 had the highest bus voltage of 1.00 p.u. This is attributed to the busses being directly connected to the generator which provides a stable power supply and minimizes the potential for voltage fluctuations as also presented by the study by

Hamzeh et al. (2018). The objective of this study was to evaluate the stability of the Solar PV-Wind HRES Grid-Tie System, therefore, stability analysis wasn't conducted for the IEEE 14-bus System. However, several studies have been performed on the stability analysis for the IEEE 14BUS System (Hashim et al., 2012; Iyambo & Tzoneva, 2007; Kumar et al., 2020; Siva et al., 2020) under different system faults and simulation software.

The Load Flow (or Power Flow) analysis is a fundamental step in power system studies, especially when integrating renewable energy sources like Solar PV and Wind resources. The primary goal of this analysis was to identify the most suitable candidate buses for incorporating these renewable resources into the grid. The criteria for selection focused on buses that were furthest from the generator but maintained a stable voltage profile, ensuring that the integration of renewable energy would enhance grid stability rather than compromise it i.e., Bus 10 for wind, Bus 12 for Solar PV, Bus 13 for wind, and Bus 14 for Solar PV as presented in Figure 4.2. In power systems, the distance of a bus from the generator can significantly influence voltage stability (Hosseinzadeh et al., 2021). Buses that are further from the generator often experience more significant voltage drops due to the increased impedance of the transmission lines (Hosseinzadeh et al., 2021; Petinrin & Shaabanb, 2016). However, if a bus far from the generator maintains a stable voltage, it suggests that the system at that location is resilient and can handle additional loads or generation without compromising overall stability (Blaabjerg et al., 2017; Hosseinzadeh et al., 2021; Ismail et al., 2020). Therefore, these buses are prime candidates for the integration of distributed generation sources such as Solar PV and Wind.

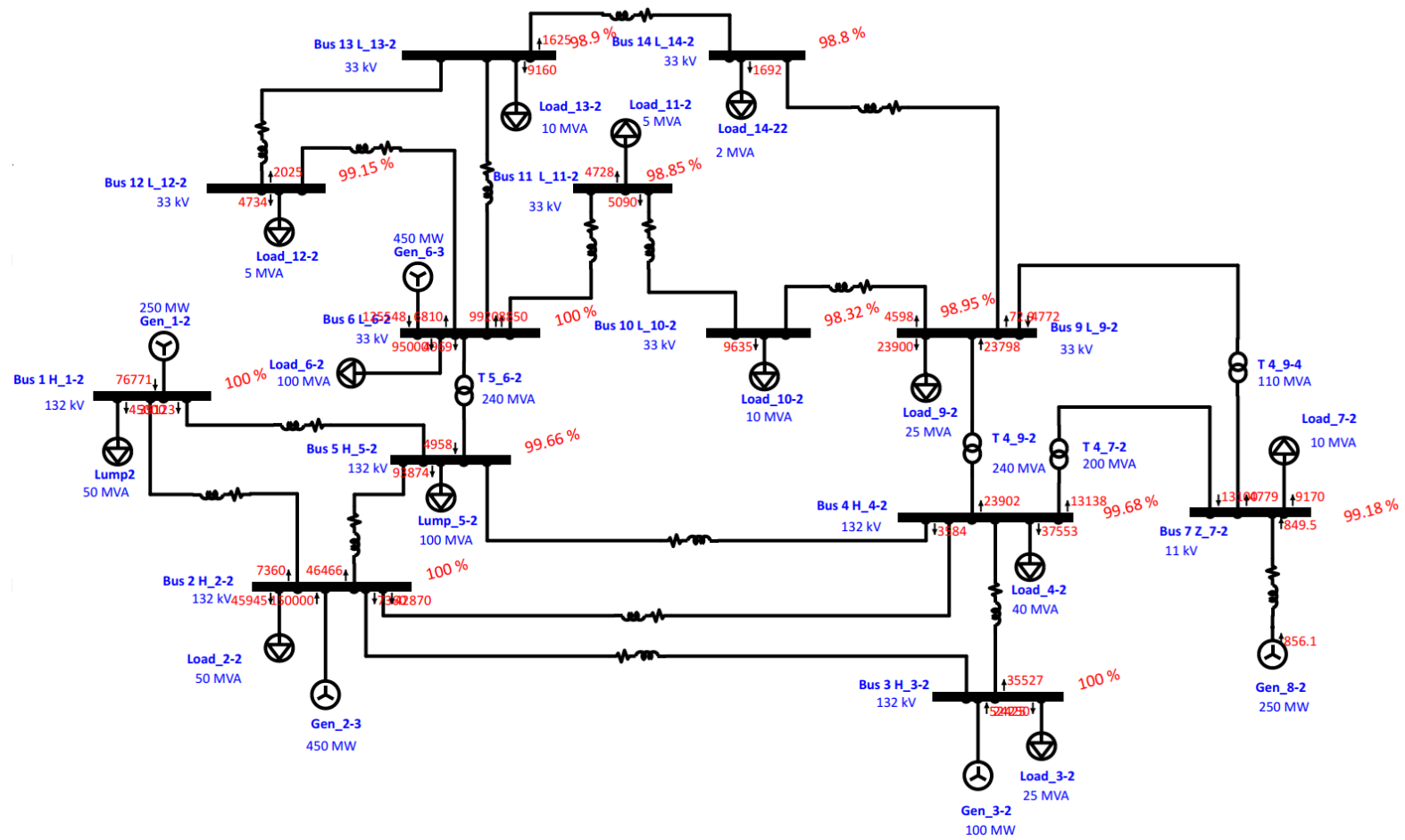


Figure 4.1: The simulated IEEE 14-bus system and Load Flow Analysis

### **4.3. Solar PV-Wind HRES Grid-Tied System**

The primary objective for the simulation of the Solar PV-Wind HRES grid tied to an IEEE 14-bus system was to analyze both transient and steady-state stability. As already mentioned, the IEEE 14-bus system was selected as the testbed for this study due to its moderate complexity and widespread use in stability analysis research (Kumar Samanta & Chanda, 2017; Liu, 2019). The system was configured to include both solar PV and wind energy sources, integrated at candidate buses to examine their impact on overall system stability as shown in Figure 4.2.

The solar PV system was connected to Bus 12 and 14 as presented in Figure 4.2. The PV system was modeled with an inverter-based interface, equipped with a Maximum Power Point Tracking (MPPT) controller to optimize power output under varying solar irradiance conditions. The PV system's capacity on Bus 12 (PV A3\_3-2) was set to 91.7 kW, with an inverter of 200 kW(DC), 180 kVA (AC), while the PV system's capacity on Bus 14 (PV A1\_14-2) was set to 113.1 kW, with an inverter of 166.7 kW(DC), 150 kVA (AC). For all the integrated PV systems a typical irradiance profile was applied to simulate day-to-day variations. Two (WTG2\_13-2 and WTG2\_10-2) 20 MW wind energy conversion systems (WECS) were connected to Bus 10 and 13, each via a 100 MVA step-up transformer. Detailed specifications of the modeled components are given in Table 3.2. The wind turbine model included a variable-speed wind turbine coupled with a doubly-fed induction generator (DFIG). The control system for the wind turbine was designed to regulate rotor speed and maintain grid stability during wind speed fluctuations.

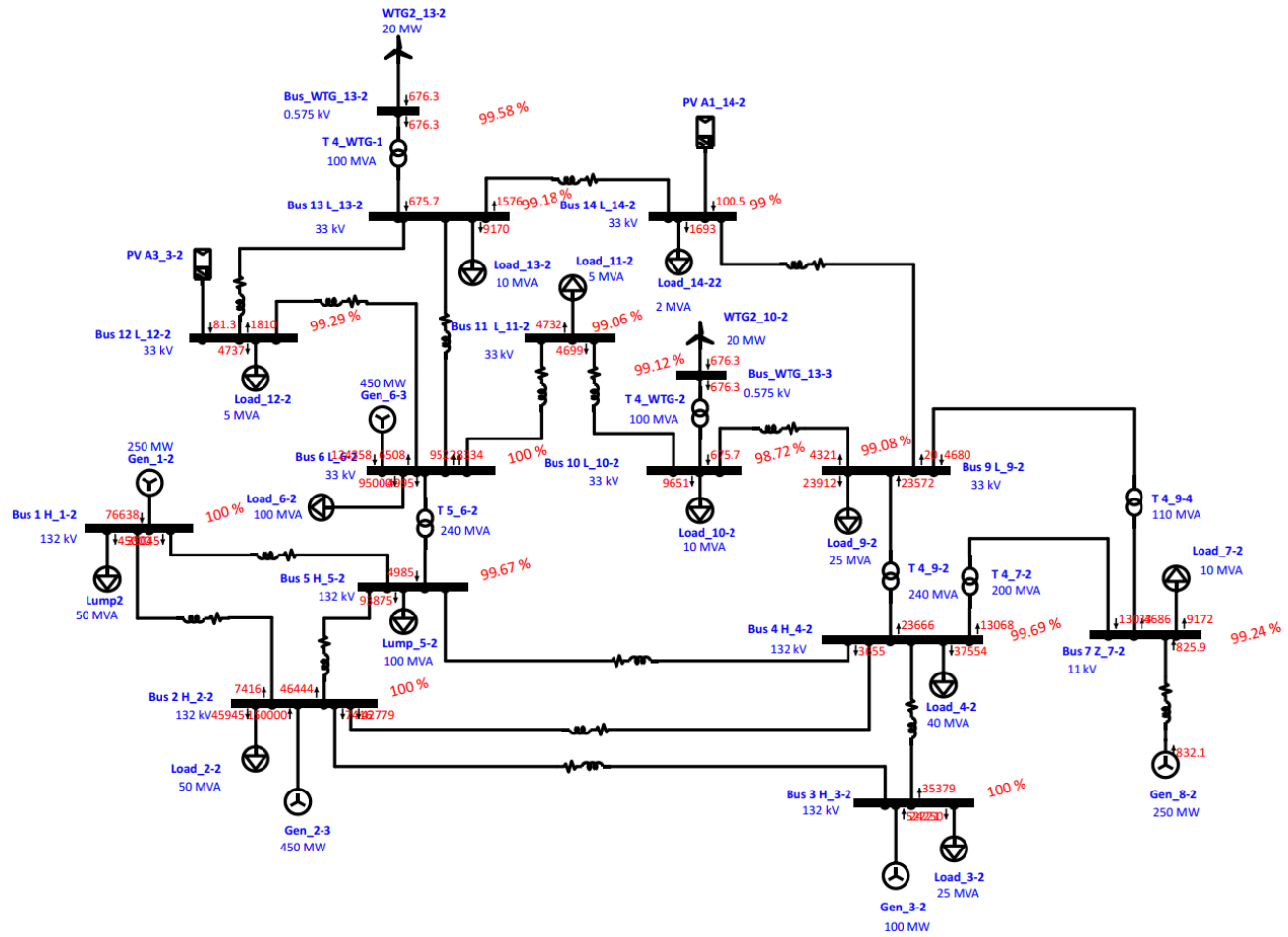


Figure 4.2: The simulated Solar PV-Wind HRES Grid-Tied System and Load Flow Analysis

The load flow analysis was conducted to establish the initial operating conditions of the IEEE 14-bus system with the integrated HRES. The following were established: Firstly, the voltages at all buses were maintained within acceptable limits (Figure 4.2), with slight variations observed at buses connected to the PV and wind systems due to their intermittent nature. The voltage at Bus 12 and 14 (connected to the PV system) was 0.9929 p.u. and 0.9999 p.u., respectively. While the voltage at Bus 10 and 13 (connected to the wind system) were 0.9878 p.u. and 0.9918 p.u., respectively. These slight variations in voltage are attributable to the intermittent nature of the PV and wind systems, which can cause fluctuations in power output depending on  $I_r$  and  $S_w$  environmental conditions (Shivashankar et al., 2016). These results are consistent with a study by Benali et al. (2018) who reported that voltage stability can be achieved by PV and Wind connected to the same point of common coupling (PCC) with a sensitive load. Similarly, Ahmed et al. (2020) discussed that integrating large PV and wind resources can improve the voltage profile of a power system. This is because these renewable energy sources can provide additional reactive power support, which helps in maintaining voltage levels within the desired range.

Secondly, the integration of PV and wind systems into the IEEE 14-bus system also resulted in noticeable changes in power flow patterns, particularly on the lines connected to Buses 10, 11, 12, 13, and 14. The power flows on these lines increased due to the additional generation from renewable sources but remained within the thermal limits of the transmission lines (Basit et al., 2020). These changes are significant because they can affect the overall load distribution and efficiency of the power system (Das et al., 2018). The power flows on these lines may increase or decrease depending on the generation from the PV and wind systems at any given time, which can lead to congestion in some lines or under-utilization of others

(Samakpong et al., 2022). Managing these power flows is essential for optimizing the performance of the grid and ensuring that it can handle the variable nature of renewable energy sources (Abdi et al., 2017; Panda & Das, 2021; Reddy, 2017).

Lastly, the integration of renewable energy sources, specifically in HRES has been found to result in a slight increase in total system losses, averaging around 0.02%. This phenomenon is primarily attributed to the additional reactive power flows introduced by the integration of renewable sources such as solar PV and wind energy systems. Reactive power, which does not perform useful work, can lead to increased losses in the system, as highlighted by (Yang et al., 2017). However, this increase is considered marginal, signifying that the overall system efficiency remains largely unaffected (Li et al., 2016). The minimal impact on system efficiency is crucial for the broader adoption of HRES (Babatunde et al., 2020). As the world moves towards sustainable energy solutions, concerns about the efficiency and reliability of these systems are paramount. The review by Roy et al. (2022) suggests that despite the slight increase in losses, the integration of HRES does not significantly compromise the system's performance. This outcome is particularly significant in the context of grid-tied systems, where maintaining high efficiency is critical to ensuring the reliability and stability of the entire power network (Shair, Li, et al., 2021; Shakerighadi et al., 2023). Moreover, the slight increase in losses can be managed and mitigated through advanced control strategies and optimization techniques (Sarkar et al., 2018). The impact of these losses can be further minimized, enhancing the overall performance of the system by fine-tuning the reactive power management and employing sophisticated grid management tools (Kow et al., 2016). This aligns with the ongoing research and development in the field of renewable energy, where the focus is not only on maximizing energy generation but also on optimizing system

performance to ensure sustainability and efficiency (Abdmouleh et al., 2017; Amran & Muhtazaruddin, 2019; Østergaard et al., 2020; Potrč et al., 2021).

#### **4.3.1. Transient stability analysis**

The transient stability analysis focused on the system's response to severe disturbances, i.e., LG at all buses and lines. The  $t_s$  and system responses were analyzed in detail. Note that the  $t_s$  is the time it takes for a response to stabilize within a small percentage (usually 5% or 2%) of its final value. For this study, the tolerance band was set to 2% to improve performance, and accuracy and reduce variability (Corneo & Jeanne, 2009).

##### **Fault on buses**

An LG fault was simulated on all the buses (one at a time) at 1.0 s and the fault was cleared at 1.05 s, 1.5 s, and 2.0 s. Figure 4.3 presents the plots for the power angles and generator speeds against time. Generally, the synchronous generators in the system exhibited significant oscillations immediately after the fault. However, the system remained stable as the oscillations dampened. Additionally, the  $t_s$  was directly proportional to the  $t_{ct}$ .

The response of synchronous generators to faults is critical in determining the overall stability of the system. The observation that the synchronous generators in the system exhibited significant oscillations immediately after the fault is consistent with typical transient responses in power systems (Xiong et al., 2020). These oscillations are a result of the sudden disturbance caused by the fault, leading to a mismatch between mechanical input power and electrical output power (Ye et al., 2016). Therefore, the system's ability to manage these oscillations determines whether it remains stable or experiences a cascading failure. Additionally, because the system remained stable as

the oscillations dampened, thus, the presence of effective damping mechanisms, either inherent within the system or due to the design of controllers like Power System Stabilizers (PSS) or other damping control strategies (Meegahapola et al., 2020; Nikolaev et al., 2021; Owais & Iqbal, 2023). Therefore, the ability of the system to return to a stable operating condition without intervention suggests that the system has a robust design capable of handling such disturbances. The relationship between  $t_s$  and  $t_{ct}$  is particularly noteworthy.  $t_{ct}$  refers to the duration between the occurrence of a fault and its isolation or clearing from the system. A direct proportionality between  $t_s$  and  $t_{ct}$  suggests that the longer the fault persists, the more prolonged the oscillations, leading to a slower return to a stable state. This relationship underscores the importance of fast and effective protection systems in minimizing fault duration to ensure the system's quick recovery and stability. These results align with findings by Yousefian et al. (2017), who explored the transient stability of power grids integrating wind farms and synchronous generators. The study found that the integration of wind energy into the power grid introduces additional dynamics that can influence stability, especially during faults. Their research emphasized the critical role of system design and control in maintaining stability, even with the added complexity of renewable energy sources. The comparison with Yousefian et al. (2017) work highlights the relevance of considering various energy sources and their impact on system stability during transient events.

Additionally, the study highlighted the critical role of fault dynamics on  $V$  and  $f$  stability in HRES. It was established that the voltage and frequency at the Bus with the fault dropped significantly during the fault but recovered to its pre-fault level after the fault was cleared. From Figure 4.4 it can be observed that during a fault event at Bus 1, both  $V$  and  $f$  experienced a substantial drop. This drop was significant during

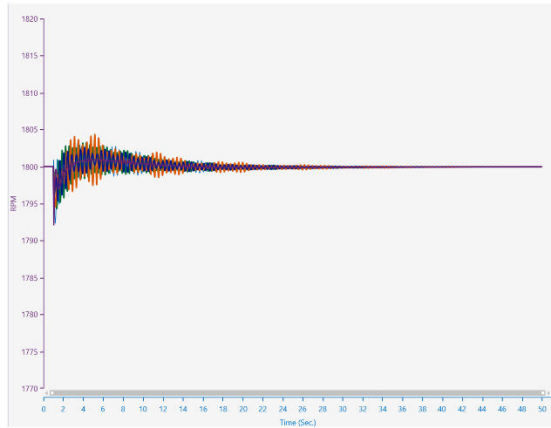
the fault but showed a notable recovery to pre-fault levels once the fault was cleared. The observed behavior underscores the inherent resilience of the system, which is designed to restore stability after disturbances (Gholami et al., 2018; Yu et al., 2020). Mojallal & Lotfifard (2017) stated that this recovery of  $V$  and  $f$  post-fault is primarily attributed to the contributions of the solar PV and wind systems. Therefore, renewable energy sources played a vital role in stabilizing the grid by injecting reactive power immediately after the fault was cleared (Morshed & Fekih, 2019). This injection of reactive power is crucial because it helps in maintaining  $V$  levels within acceptable limits, thereby facilitating the restoration of  $f$  to its nominal value (Hasheminamin et al., 2018). The study further established that the extent of  $V$  and  $f$  drops during the fault was significantly influenced by the  $t_{ct}$ . A larger  $t_{ct}$  was associated with a more pronounced drop in both  $V$  and  $f$ . Similarly, this finding is critical because it highlights the importance of rapid fault detection and clearance mechanisms in minimizing the adverse effects of faults on grid stability. The longer the fault persists, the more severe the  $V$  and  $f$  deviations, which can pose serious challenges to grid stability and reliability.

The relationship between  $t_{ct}$  and the severity of  $V$  and  $f$  drops can be explained by the delayed response of the renewable energy systems in injecting reactive power (Basit et al., 2020; Mlilo et al., 2021; Stanelytė & Radziukynas, 2022). Therefore, when the fault is cleared quickly, renewable sources can respond almost immediately, minimizing the impact on the grid (Basit et al., 2020). Conversely, a delayed clearance means that the system operates under fault conditions for a longer period, leading to more significant disruptions before stabilization efforts can take effect (Morshed & Fekih, 2019).

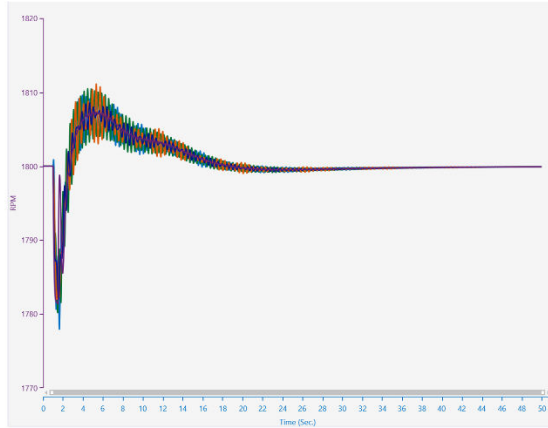
### **Fault on Transmission Lines**

Similarly, an LG fault was simulated on all the transmission lines (one at a time) at 1.0 s and the fault was cleared at varied  $t_{ct}$  of 1.05 s, 1.5 s, and 2.0 s. Additionally, in the simulation the  $F_p$  was varied at intervals from 0% to 100% of the line length. Figure 4.5 presents the plots for the power angles and generator speeds against time at a  $F_p$  of 50%. It can be observed that at a  $t_{ct}$  of 1.05 seconds, the oscillations within the system are sufficiently dampened, allowing the generators to regain stability. This implies that a timely clearance of faults is critical for maintaining the operational stability of the system (Nsaif et al., 2021). Specifically, when faults are cleared within this time frame, the system's transient stability is preserved (James et al., 2017), and the oscillatory behavior of the power angles is mitigated, leading to a steady-state condition where the generators can continue functioning without being isolated from the grid (Meegahapola et al., 2020).

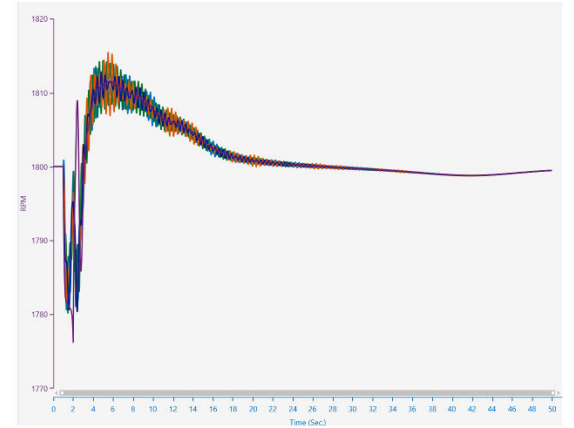
However, when the  $t_{ct}$  is extended beyond 1.05 seconds, a different dynamic unfolds. As depicted in Figures 4.5(e) and (f), generators connected to the faulted line are eventually isolated from the system (Nagpal & Henville, 2017). This isolation occurs because the extended presence of the fault leads to more pronounced oscillations in the system, making it difficult for the generators to maintain synchrony with the rest of the grid (Auer et al., 2017).



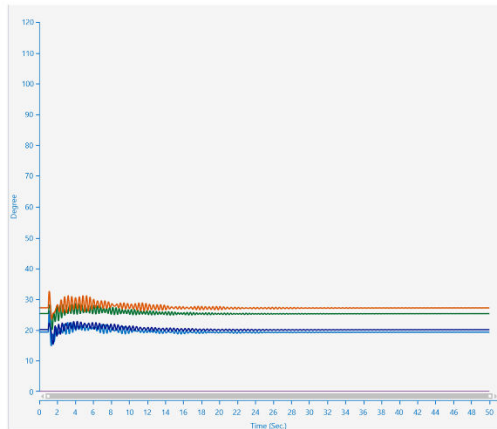
(a)



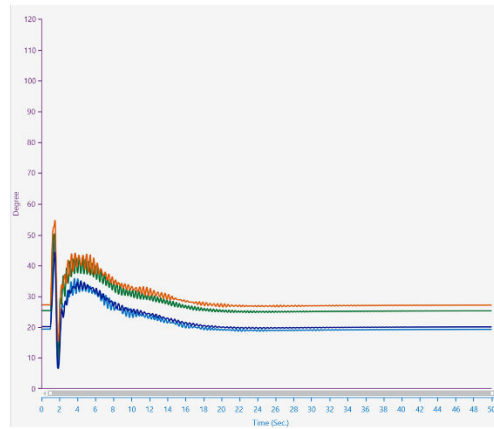
(b)



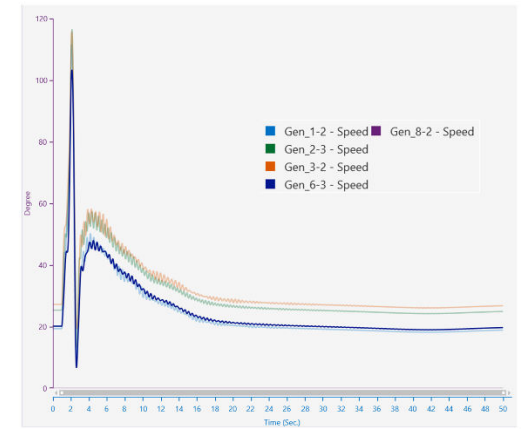
(c)



(d)



(e)



(f)

Figure 4.3: The plots for Power angle and Speed for the synchronous generators with a fault on Bus 1, (a) Speed at  $t_{ct} = 1.05$  s, (b) Speed at  $t_{ct} = 1.50$  s, (c) Speed at  $t_{ct} = 2.00$  s, (d) Power angle at  $t_{ct} = 1.05$  s, (e) Power angle at  $t_{ct} = 1.50$  s, (f) Power angle at  $t_{ct} = 2.00$  s.

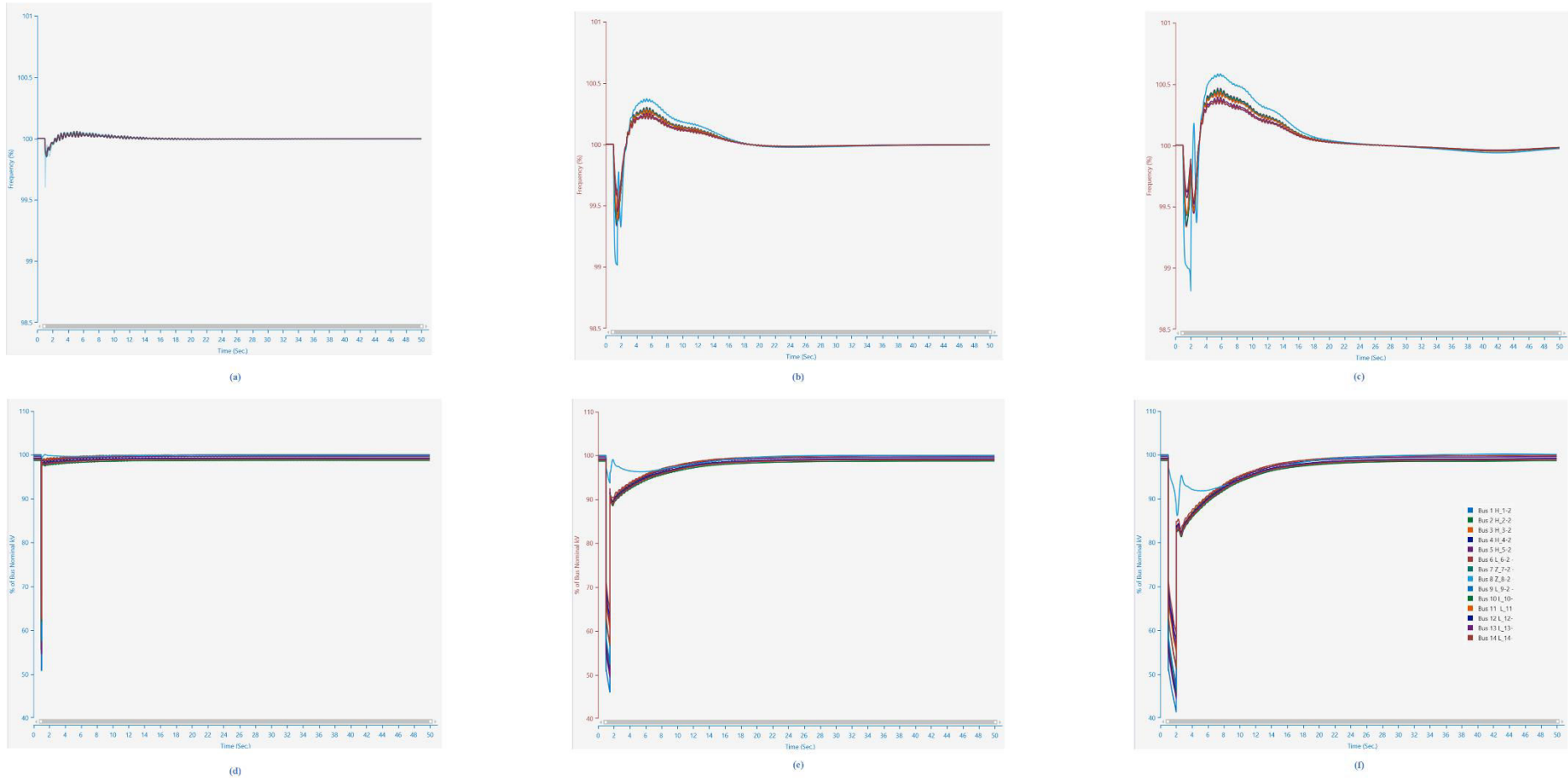


Figure 4.4: The plots for Frequency and Voltage for the synchronous generators with a fault on Bus 1, (a) Frequency at  $t_{ct} = 1.05$  s, (b) Frequency at  $t_{ct} = 1.50$  s, (c) Frequency at  $t_{ct} = 2.00$  s, (d) Voltage at  $t_{ct} = 1.05$  s, (e) Voltage at  $t_{ct} = 1.50$  s, (f) Voltage at  $t_{ct} = 2.00$  s.

The instability is further evidenced by the power angle oscillations, which begin to swing between positive and negative values, as shown in Figures 4.5(b) and (c). These oscillations indicate a loss of synchronism, which is a precursor to the generators being disconnected from the network to prevent further damage or instability in the broader system (Sharafutdinov et al., 2018).

The effect of  $F_p$  and  $t_{ct}$  was also analyzed to determine the effect of the  $F_p$  and  $t_{ct}$  on system stability based on  $f$  and  $V$ . From the Figure 4.6 and 4.7, it can be observed that  $F_p$  doesn't have much effect on the  $f$  and  $V$  profiles. Therefore, the location of the fault on a transmission line does not significantly alter the system's voltage and frequency characteristics (Chen et al., 2016; Chen et al., 2017). However, the  $t_{ct}$  had a noticeable effect. i.e., the  $t_s$  of 1.50 s and 2.00 s were longer compared to those of 1.05 s. This indicates that the duration it takes to clear a fault is crucial in determining the system's ability to return to stable  $f$  and  $V$  levels. The increased  $t_s$  associated with longer fault clearance intervals suggest that delays in clearing faults can exacerbate instability and prolong the recovery process (Wang et al., 2016).

#### **4.3.2. Steady-state stability analysis**

Steady-state stability analysis is a crucial aspect of assessing the performance of a power system under normal operating conditions and minor disturbances. Regarding Solar PV-Wind Hybrid HRES grid-tied to an IEEE 14-bus system, this analysis focused on the system's ability to maintain equilibrium under small perturbations, i.e., gradual changes in generation.

The simulation results indicate that the integration of Solar PV and WECS into the IEEE 14-bus system resulted in minor  $V$  fluctuations, though the system maintained voltages within  $\pm 2\%$  of the nominal 1.0 p.u. standard (Djalal et al., 2024). This

outcome aligns with the findings of several studies that emphasize the resilience of modern power systems in accommodating renewable energy sources, despite their inherent variability (Jones, 2017; Ma et al., 2021; Smith et al., 2022). Specifically, the voltages at Buses 12 and 14, where the Solar PV systems were integrated, ranged between 1.01 p.u. and 0.97 p.u., reflecting the fluctuations in solar irradiance. Similarly, the voltages at Buses 10 and 13, which hosted the WECS, varied between 1.02 p.u. and 0.97 p.u. due to changes in wind speed. These fluctuations are consistent with the expected behavior of renewable energy systems, where variations in natural energy inputs directly affect power output and, consequently, bus voltages (Bessa et al., 2019; Hosseinzadeh et al., 2021; Mararakanye & Bekker, 2019; Mlilo et al., 2021).

Table 4.1: The Voltage Stability Index (VSI) for each bus

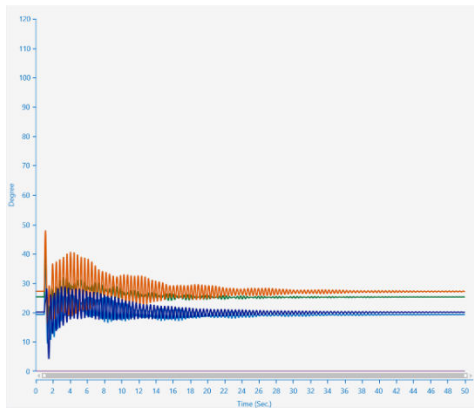
<b>Bus</b>	<b>Voltage Stability Index (VSI)</b>
Bus 1	0.12
Bus 2	0.12
Bus 3	0.14
Bus 4	0.11
Bus 5	0.20
Bus 6	0.11
Bus 7	0.21
Bus 8	0.14
Bus 9	0.29
Bus 10	0.42
Bus 11	0.30
Bus 12	0.35
Bus 13	0.32
Bus 14	0.33

Additionally, the computation of the Voltage Stability Index (VSI) provided insights into the system's proximity to voltage instability (Yadav et al., 2024). The VSI values, which indicate stability when close to zero and instability when approaching one (Modarresi et al., 2016), revealed that Bus 10 had the highest VSI of 0.42 as shown in Table 4.1. Although this value is within the stable range, it suggests that the integration of renewable energy at this bus could be approaching a threshold where voltage instability becomes a concern, particularly with increased penetration levels.

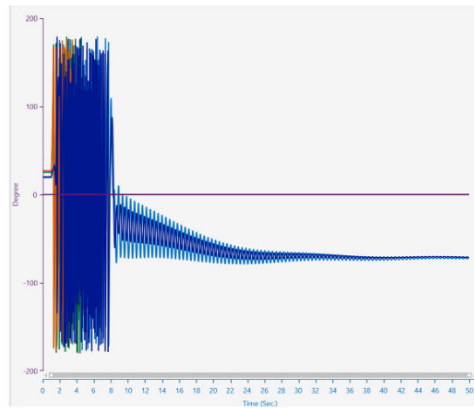
Therefore, it is important to monitor and manage voltage stability in systems with high renewable energy penetration to ensure reliable operation (Hosseinzadeh et al., 2021). This is critical as the proportion of renewable energy in power systems continues to grow, necessitating advanced control strategies to mitigate potential stability issues (Rahman et al., 2021).

Furthermore, the results demonstrate the stability and robustness of the HRES, despite inherent fluctuations in the output of its components. The PV system's output varied by approximately  $\pm 20\%$  due to changes in  $I_r$ , while the wind turbine's output fluctuated by about  $\pm 15\%$  due to variations in  $S_w$ . Such fluctuations are typical in renewable energy sources, which are highly dependent on environmental conditions (Liang, 2016). Despite these variations, the overall system remained stable, as evidenced by the lack of significant  $f$  or  $V$  deviations. This stability is crucial for grid-tied systems, where  $f$  and  $V$  must be maintained within strict limits to ensure reliable operation and compatibility with the grid (Obi & Bass, 2016).

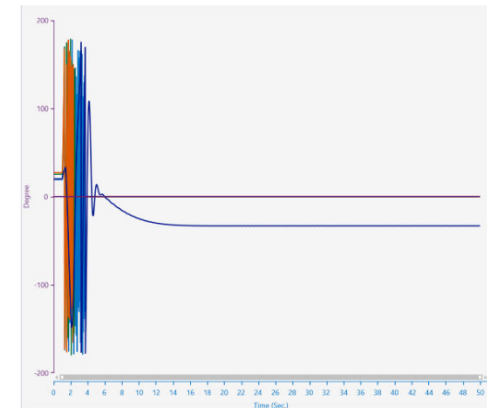
The eigenvalue analysis further supports the above system's stability results. All eigenvalues were located in the left half of the complex plane, indicating a stable system (Stone, 2018). Eigenvalues close to the imaginary axis represent the slowest modes of the system, which are influenced primarily by the control dynamics of renewable sources (Machowski et al., 2020). The presence of these slow modes suggests that the system's response to disturbances is dominated by the behavior of the renewable energy control systems (Liu et al., 2020; Machowski et al., 2020). Moreover, the system exhibited adequate damping, with a minimum damping ratio of 0.15.



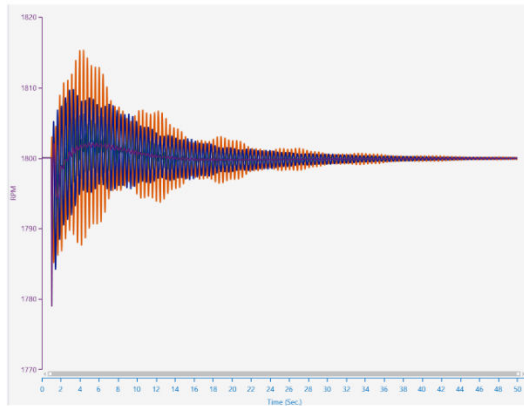
(a)



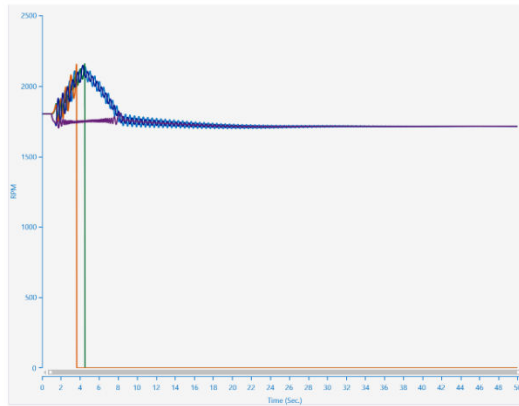
(b)



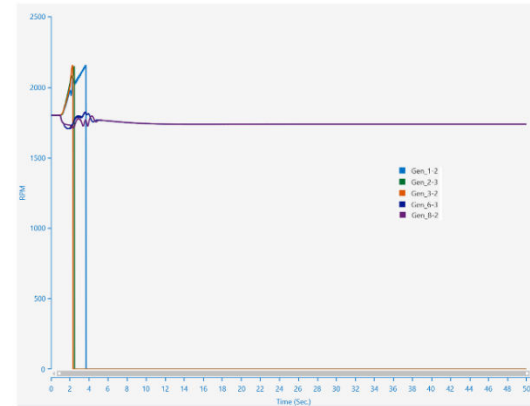
(c)



(d)



(e)



(f)

Figure 4.5: The plots for Power angle and Speed for the synchronous generators with a fault on transmission Line 1 at 50% fault position, (a) Power angle at  $t_{ct} = 1.05$  s, (b) Power angle at  $t_{ct} = 1.50$  s, (c) Power angle at  $t_{ct} = 2.00$  s, (d) Speed at  $t_{ct} = 1.05$  s, (e) Speed at  $t_{ct} = 1.50$  s, (f) Speed at  $t_{ct} = 2.00$  s

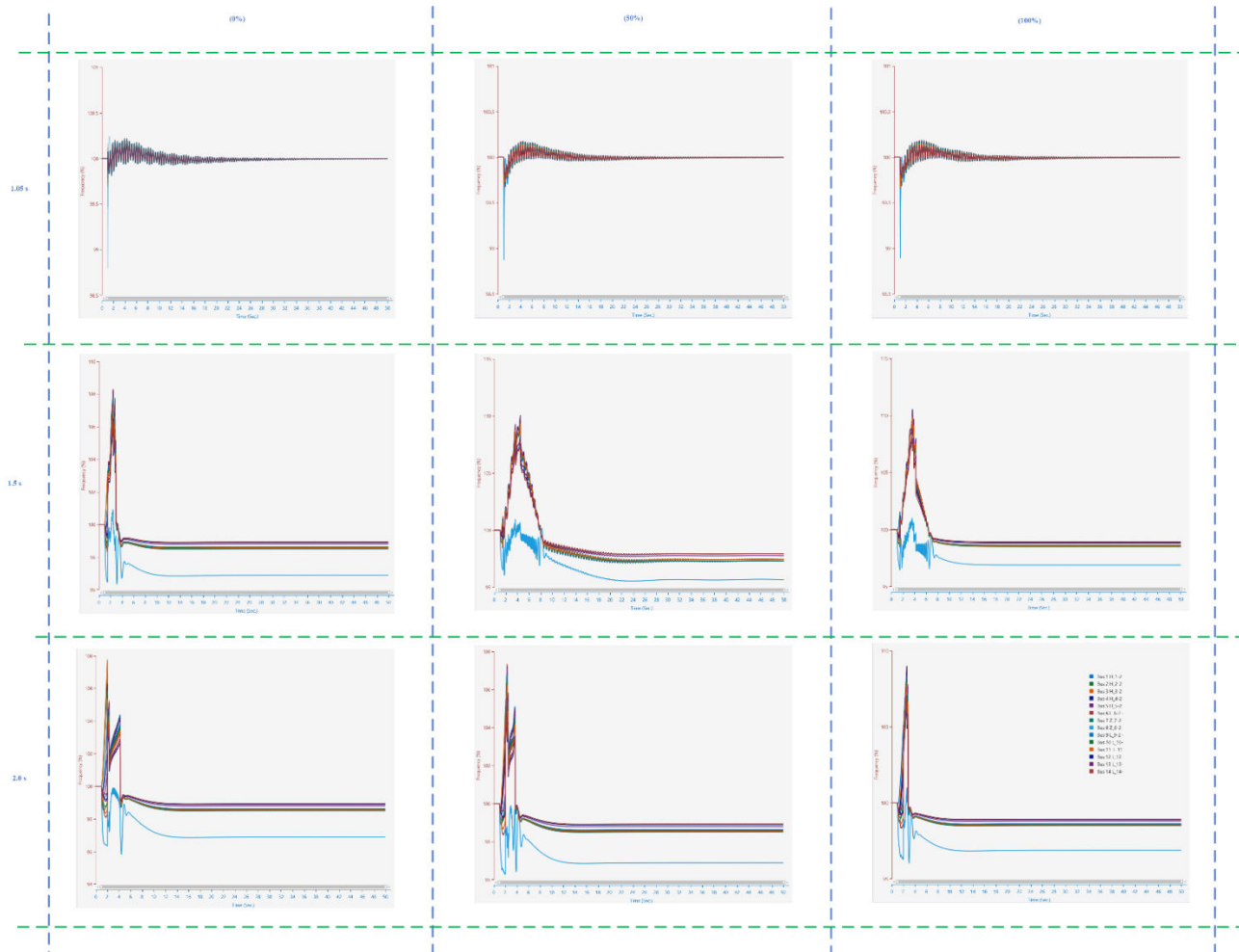


Figure 4.6: The plots for Frequency at different  $F_p$  and  $t_{ct}$

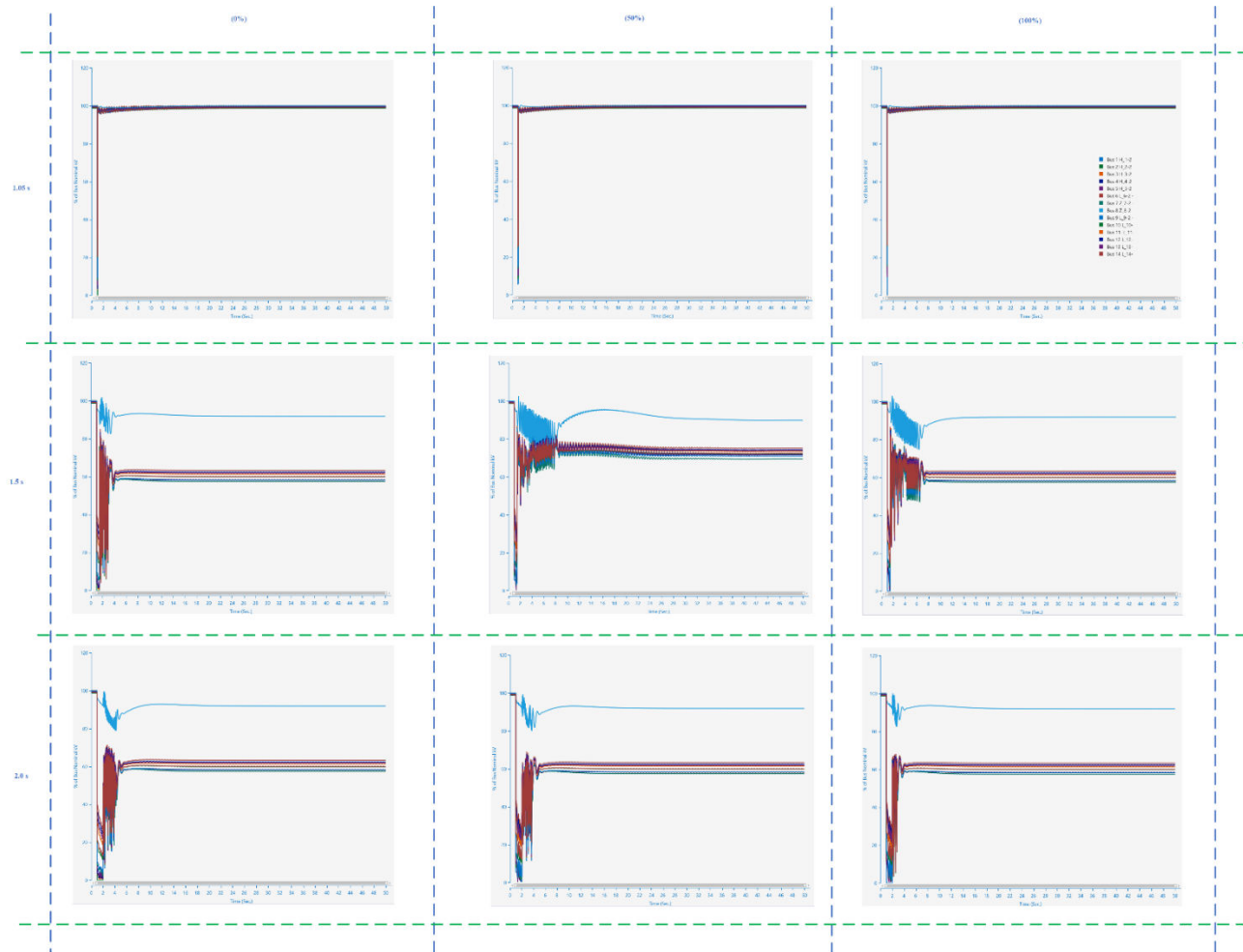


Figure 4.7: The plots for Voltage at different  $F_p$  and  $t_{ct}$



the mean  $t_s$  for  $V$  was 14.810 s with a median of 5.551 s ranging from 1.021 s (minimum) to 50.000 s (maximum).

Table 4.2: The descriptive statistics of the setting time for generator speed bus frequency and bus voltage without (BESS)( $n = 4060$ ).

<b>Descriptive statistics</b>	<b>Speed (s)</b>	<b>Frequency (s)</b>	<b>Voltage (s)</b>
Maximum	50.000	1.050	50.000
Minimum	1.021	49.981	1.021
Range	48.9794	48.931	48.979
Interquartile Range	19.030	9.170	17.010
Median	6.596	5.991	5.551
Skewness	1.083	2.237	1.282
Mean	15.843	8.898	14.810
Standard error	0.283	0.168	0.268
Standard deviation	18.050	10.732	17.052
Variance	325.807	115.168	290.776

The Shapiro-Wilk Test of Normality revealed that the initial dataset was not normally distributed, which is crucial because many statistical analyses assume normality to yield valid results (Shapiro & Wilk, 1965). The test's outcome indicates a deviation from the normal distribution, as further evidenced by the positive skewness reported in Table 4.2. A positively skewed distribution suggests that the data has a longer tail on the right side, meaning that higher values are more spread out (Rousselet & Wilcox, 2018). Therefore, a logarithmic (Log) transformation was applied to the data. This transformation is a common technique used to normalize data, especially when dealing with positively skewed distributions (Lee, 2020). After the transformation, the Shapiro-Wilk Test was reapplied, confirming that the transformed data met the normality assumption. This process of transformation and re-testing is vital to ensure that the subsequent analyses, which rely on the assumption of normality, are valid and reliable. Thus, the log transformation effectively mitigated the skewness, enabling the

data to conform to the assumptions required for further statistical procedures (Knief & Forstmeier, 2021; Lee, 2020).

### Fault on buses

For each variable, i.e.,  $f$ ,  $V$ , and  $G_s$ , the  $t_s$  was analyzed as presented in Table 4.3. Firstly, a one-way ANOVA was conducted to examine the effect of  $t_{ct}$  on  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $V$ . It was established that there was a statistically significant difference between  $t_{ct} = 1.05\text{ s}$ ,  $t_{ct} = 1.50\text{ s}$ , and  $t_{ct} = 2.00\text{ s}$  groups ( $p < 0.05$ ). A Tukey post hoc test revealed that  $t_s$  was statistically significantly lowest for  $t_{ct} = 1.05\text{ s}$  and highest for  $t_{ct} = 2.00\text{ s}$  ( $p < 0.05$ ). These results ascertain that a shorter  $t_{ct}$  leads to faster  $V$  stabilization, which could be indicative of a more robust system response to disturbances. However, there was no statistically significant difference between the  $t_{ct} = 1.50\text{ s}$ , and  $t_{ct} = 2.00\text{ s}$  groups. This implies that after a certain threshold, increasing  $t_{ct}$  does not further delay the system's  $V$  response significantly.

Table 4.3: The statistical results of the settling time ( $t_s$ ) expressed in terms of mean and standard deviation without BESS

Fault clearance time ( $t_{ct}$ )	$f(t_s)$	$V(t_s)$	$G_s(t_s)$
$t_{ct} = 1.05\text{ s}$	$5.316 \pm 0.448^a$	$10.696 \pm 0.587^a$	$11.108 \pm 0.549^a$
$t_{ct} = 1.50\text{ s}$	$7.379 \pm 0.491^b$	$12.526 \pm 0.404^b$	$14.256 \pm 0.605^b$
$t_{ct} = 2.00\text{ s}$	$9.315 \pm 0.509^b$	$12.438 \pm 0.591^b$	$15.005 \pm 0.628^b$

a, b mean  $\pm$  std within a column with no superscript in common differ significantly ( $p < 0.05$ )

Secondly, a one-way ANOVA was conducted that examined the effect of  $t_{ct}$  on  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $f$ . Similarly, it was established that there was a statistically significant difference between  $t_{ct} = 1.05\text{ s}$ ,  $t_{ct} = 1.50\text{ s}$ , and  $t_{ct} = 2.00\text{ s}$  groups ( $p < 0.05$ ). A Tukey post hoc test revealed that  $t_s$  was statistically significantly lowest for  $t_{ct} = 1.05\text{ s}$  and highest for

$t_{ct} = 2.00$  s ( $p < 0.05$ ). However, there was no statistically significant difference between the  $t_{ct} = 1.50$  s, and  $t_{ct} = 2.00$  s groups. The lack of a significant difference between the 1.50 s and 2.00 s  $t_{ct}$  groups suggest a plateau in the impact of  $t_{ct}$  on frequency stabilization beyond a certain point. The observed trend across both  $V$  and  $f$  analyses indicates that a shorter critical clearing time is generally associated with quicker system stabilization, which is crucial in maintaining grid reliability and preventing cascading failures (Guo et al., 2017).

Table 4.4: A summary of the data on the effect of fault position ( $F_p$ ) and fault clearance time ( $t_{ct}$ ) on settling time ( $t_s$ ) for Frequency ( $f$ ), voltage ( $V$ ) and generator speed ( $G_s$ ) (without BESS)

$F_p$	$t_{ct}$	$f(t_s)$	$V(t_s)$	$G_s(t_s)$
0% mean $\pm$ std	$t_{ct} = 1.05$ s	$2.608 \pm 0.253$	$1.381 \pm 0.138$	$1.841 \pm 0.218$
	$t_{ct} = 1.50$ s	$11.545 \pm 0.261$	$7.687 \pm 0.193$	$11.738 \pm 0.306$
	$t_{ct} = 2.00$ s	$24.575 \pm 0.436$	$12.296 \pm 0.472$	$27.853 \pm 0.524$
10% mean $\pm$ std	$t_{ct} = 1.05$ s	$2.522 \pm 0.245$	$1.489 \pm 0.137$	$1.813 \pm 0.204$
	$t_{ct} = 1.50$ s	$14.459 \pm 0.330$	$9.235 \pm 0.175$	$16.132 \pm 0.356$
	$t_{ct} = 2.00$ s	$33.709 \pm 0.482$	$18.629 \pm 0.440$	$34.360 \pm 0.482$
25% mean $\pm$ std	$t_{ct} = 1.05$ s	$2.657 \pm 0.259$	$1.496 \pm 0.147$	$1.768 \pm 0.197$
	$t_{ct} = 1.50$ s	$17.027 \pm 0.283$	$10.421 \pm 0.246$	$18.801 \pm 0.398$
	$t_{ct} = 2.00$ s	$25.226 \pm 0.465$	$21.407 \pm 0.441$	$30.560 \pm 0.455$
50% mean $\pm$ std	$t_{ct} = 1.05$ s	$2.394 \pm 0.229$	$1.560 \pm 0.150$	$1.832 \pm 0.199$
	$t_{ct} = 1.50$ s	$12.170 \pm 0.287$	$8.5168 \pm 0.127$	$12.704 \pm 0.297$
	$t_{ct} = 2.00$ s	$31.419 \pm 0.458$	$16.619 \pm 0.495$	$32.010 \pm 0.502$
75% mean $\pm$ std	$t_{ct} = 1.05$ s	$2.430 \pm 0.239$	$1.545 \pm 0.147$	$1.662 \pm 0.179$
	$t_{ct} = 1.50$ s	$11.987 \pm 0.279$	$7.435 \pm 0.166$	$12.216 \pm 0.300$
	$t_{ct} = 2.00$ s	$30.620 \pm 0.456$	$14.874 \pm 0.549$	$31.338 \pm 0.534$
90% mean $\pm$ std	$t_{ct} = 1.05$ s	$2.728 \pm 0.243$	$1.617 \pm 0.160$	$1.958 \pm 0.211$
	$t_{ct} = 1.50$ s	$12.388 \pm 0.286$	$8.414 \pm 0.158$	$13.017 \pm 0.291$
	$t_{ct} = 2.00$ s	$28.761 \pm 0.508$	$17.772 \pm 0.587$	$33.626 \pm 0.554$
100% mean $\pm$ std	$t_{ct} = 1.05$ s	$2.964 \pm 0.262$	$1.519 \pm 0.165$	$2.170 \pm 0.246$
	$t_{ct} = 1.50$ s	$10.639 \pm 0.275$	$8.196 \pm 0.180$	$11.252 \pm 0.283$
	$t_{ct} = 2.00$ s	$29.020 \pm 0.497$	$14.490 \pm 0.551$	$33.981 \pm 0.538$

Lastly, a one-way ANOVA was conducted that examined the effect of  $t_{ct}$  on  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $G_s$ . Similarly, it was established that there was a statistically significant difference between  $t_{ct} = 1.05$  s,  $t_{ct} = 1.50$  s, and  $t_{ct} = 2.00$  s groups ( $p < 0.05$ ). A Tukey post hoc test

revealed that  $t_s$  was statistically significantly lowest for  $t_{ct} = 1.05$  s and highest for  $t_{ct} = 2.00$  s ( $p < 0.05$ ). However, there was no statistically significant difference between the  $t_{ct} = 1.50$  s, and  $t_{ct} = 2.00$  s groups. Generally, this consistent pattern across all the analyzed stability parameters underscores the critical role of  $t_{ct}$  in determining the dynamic performance of the HRES. The  $f$ ,  $V$ , and  $G_s$ , shows that shorter  $t_{ct}$  are beneficial for system stability, as they reduce the duration of disturbances and allow the system to return to steady-state operation more rapidly.

The results of these analyses indicate a clear relationship between  $t_{ct}$  and the stabilization times of  $f$ ,  $V$ , and  $G_s$  in a Solar-PV-Wind HRES grid tied to an IEEE 14 bus system. Across all three parameters, shorter  $t_{ct}$  values consistently led to faster stabilization times, which is advantageous for maintaining system stability during transient disturbances. The lack of significant differences between  $t_{ct} = 1.50$  s, and  $t_{ct} = 2.00$  s suggests that while extending  $t_{ct}$  beyond 1.50 s may not yield further benefits in stabilization time, reducing  $t_{ct}$  below this threshold is critical for optimal system performance. These findings highlight the importance of carefully selecting  $t_{ct}$  to ensure both the reliability and efficiency of hybrid renewable energy systems connected to the grid.

### **Fault on Transmission Lines**

As already mentioned, the fault on the transmission line was varied at different  $F_p$  as the fault was cleared at varying  $t_{ct}$  a summary of the data is given in Table 4.4. For each variable, i.e.,  $f$ ,  $V$ , and  $G_s$ , the  $t_s$  was analyzed as presented in Table 4.5.

Firstly, a two-way ANOVA was conducted that examined the effect of  $t_{ct}$  and  $F_p$  on  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $V$ . There was a statistically significant interaction between the effects of  $t_{ct}$  and  $F_p$  on the  $t_s$  of

( $p < 0.05$ ). thus, the combined effect of  $t_{ct}$  and  $F_p$  on the  $t_s$  of  $V$  is more complex than the individual effects of these factors. However, there was no statistically significant difference in the  $F_p$  on the  $t_s$  of ( $p < 0.05$ ). Indicating that variations in  $F_p$  do not independently influence the  $V$  stability significantly. Additionally, there was a statistically significant difference in the  $t_{ct}$  on the  $t_s$  of ( $p < 0.05$ ), with  $t_{ct} = 2.00$  s having a significantly higher  $t_s$  than all the other  $t_{ct}$ . Therefore, a longer  $t_{ct}$  could lead to more extended periods before  $V$  stability is re-established after a disturbance.

Secondly, a two-way ANOVA was conducted that examined the effect of  $t_{ct}$  and  $F_p$  on the  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $f$ . There was a statistically significant interaction between the effects of  $t_{ct}$  and  $F_p$  on the  $t_s$  of ( $p < 0.05$ ). This indicates that the interaction between these factors critically affects how quickly the system  $f$  stabilizes after a disturbance. A simple main effects analysis showed that  $t_{ct} = 2.00$  s had a significantly higher  $t_s$  than  $t_{ct} = 1.05$  s and  $t_{ct} = 1.50$  s for all  $F_p$ . This finding reinforces the notion that larger  $t_{ct}$  are associated with delayed stabilization across different  $F_p$  levels. Additionally, there were statistically significant differences between  $F_p$  1 (0%) and  $F_p$  2 (10%),  $F_p$  3 (25%),  $F_p$  4 (50%), and  $F_p$  6 (90%), between  $F_p$  2(10%) and  $F_p$  7 (100%), between  $F_p$  3(25%) and  $F_p$  5 (75%) and  $F_p$  6 (90%), between  $F_p$  7(100%) and  $F_p$  3 (25%) and 4 (50%) on the  $t_s$  of  $f$  ( $p < 0.05$ ). These differences highlight the influence of  $F_p$  levels on  $f$  stability, suggesting that as the  $F_p$  level increases, the time required for the  $f$  to settle also changes, although the relationship is not strictly linear.

Lastly, a two-way ANOVA was conducted that examined the effect of  $t_{ct}$  and  $F_p$  on the  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $G_s$ . It was established that there was a statistically significant interaction between the effects of  $t_{ct}$  and  $F_p$  on the  $t_s$  of  $G_s$  ( $p < 0.05$ ). This interaction underscores the complex dynamics that dictate  $G_s$  stability, influenced by both  $t_{ct}$  and  $F_p$  level. Similar to the findings for  $V$  and  $f$  the simple main effects analysis showed that  $t_{ct} = 2.00$  s had a significantly higher  $t_s$  than  $t_{ct} = 1.05$  s and  $t_{ct} = 1.50$  s for all  $F_p$ . This consistent trend across all examined parameters suggests that  $t_{ct}$  of 2.00 s is particularly detrimental to the system's ability to quickly stabilize, regardless of the  $F_p$  level. Moreover, there were statistically significant differences between  $F_p$  1 (0%) and all the other  $F_p$  ( $p < 0.05$ ). This finding indicates that any increase in  $F_p$  beyond 0% significantly affects the time it takes for  $G_s$  to stabilize, further emphasizing the sensitivity of the system's mechanical dynamics to  $F_p$  levels.

Table 4.5: The statistical results of the settling time ( $t_s$ ) expressed in terms of mean and standard deviation (without BESS)

Fault position ( $F_p$ )	$f$ ( $t_s$ )	$V$ ( $t_s$ )	$G_s$ ( $t_s$ )
0% mean $\pm$ std	7.121 $\pm$ 0.468 <sup>g</sup>	12.909 $\pm$ 0.491	13.811 $\pm$ 0.572 <sup>a</sup>
10% mean $\pm$ std	9.577 $\pm$ 0.502 <sup>d<sup>ef</sup></sup>	16.097 $\pm$ 0.557	17.043 $\pm$ 0.617 <sup>b</sup>
25% mean $\pm$ std	11.108 $\pm$ 0.530 <sup>d</sup>	14.991 $\pm$ 0.531	17.069 $\pm$ 0.610 <sup>b</sup>
50% mean $\pm$ std	9.092 $\pm$ 0.488 <sup>ad</sup>	15.641 $\pm$ 0.536	15.633 $\pm$ 0.586 <sup>b</sup>
75% mean $\pm$ std	8.092 $\pm$ 0.478 <sup>aceg</sup>	15.317 $\pm$ 0.533	15.375 $\pm$ 0.598 <sup>b</sup>
90% mean $\pm$ std	9.268 $\pm$ 0.506 <sup>acf</sup>	14.626 $\pm$ 0.516	16.200 $\pm$ 0.594 <sup>b</sup>
100% mean $\pm$ std	8.068 $\pm$ 0.494 <sup>b<sup>cg</sup></sup>	14.208 $\pm$ 0.503	15.801 $\pm$ 0.583 <sup>b</sup>

a, b mean  $\pm$  std within a column with no superscript in common differ significantly ( $p < 0.05$ )

#### 4.4. Solar PV-Wind-Battery HRES System

For comparative analysis, the Solar PV-Wind-battery system was modeled as the battery was integrated on the Buses with Solar PV, i.e., Bus 12 and 14 as shown in Figure 4.9. These Buses were selected because BESS is designed to manage short-

term fluctuations in power output from renewable sources and provide support during disturbances (Ku & Li, 2021). The BESS was modeled with a charger, inverter, and Battery. All the batteries (Battery\_1 and Battery\_2) were 1350 AH. The charger on Bus 12 (Charger\_2) was set to 5kVA with an inverter of 150 kW (DC), 135 kVA (AC). The charger on Bus 14 (Charger\_1) was set to 5kVA with an inverter of 250 kW (DC), 225 kVA (AC). Detailed specifications of the modeled components and integration are given in Table 3.2.

The objectives were to analyze the power distribution, bus voltages, and line losses within the system. Therefore, the load flow analysis was performed to determine the steady-state operating conditions of the IEEE 14-bus system with the integration of the Solar PV-Wind-Battery HRES. As was already observed, the integration of the HRES into the IEEE 14-bus system significantly altered the power flow across the network. The Solar PV and wind turbines were modeled as distributed generation sources connected to specific buses, while the BESS was also integrated to manage the variability of renewable generation. The load flow results showed that the power generated by the PV and wind systems was effectively distributed across the buses, reducing the power demand on the conventional generators as shown in Figure 4.9. Therefore, the BESS played a crucial role in balancing the power flow, particularly during periods of low renewable generation or sudden load changes. Additionally, the voltage profile across the 14 buses was monitored to ensure that all bus voltages remained within acceptable limits (0.97 to 1.00 p.u.).

The simulation results demonstrate the significant role of BESS in enhancing the stability and efficiency of a Solar PV-wind HRES. Specifically, the integration of BESS helps maintain a stable voltage profile across the network, with voltages ranging from 0.98772 to 1.000 p.u. This stability is crucial for the reliable operation

of the grid, ensuring that voltage levels remain within acceptable limits, which is vital for both the protection of equipment and the consistent delivery of power to end-users (Bignucolo et al., 2017). The observed stability in bus voltages is particularly noteworthy given the inherent variability of renewable energy sources such as solar and wind. These sources are often characterized by fluctuations in power generation, which can lead to voltage instability, especially during periods of high load or low generation (Petinrin & Shaabanb, 2016). The minor deviations in voltage at buses connected to renewable energy sources during these periods underscore the challenges posed by the integration of renewables (Azizipanah-Abarghooee et al., 2024). However, the presence of BESS mitigates these deviations by providing a buffer that compensates for the variability, thereby maintaining the overall voltage stability of the system (Ehsan & Yang, 2018). Another significant benefit of integrating BESS into the Solar PV-Wind hybrid system is the reduction in line losses. The simulation results indicate an average reduction of 1.25% in line losses compared to the system without BESS. This reduction is attributable to the strategic placement of distributed generation sources close to load centers (Sultana et al., 2016). When power is generated closer to where it is consumed, transmission losses are minimized, thereby enhancing the overall efficiency of the system (Prakash & Khatod, 2016; Sultana et al., 2016). This principle is supported by multiple studies, which have consistently shown that proximity between generation and consumption points leads to lower transmission losses (Abdmouleh et al., 2017; Ehsan & Yang, 2018; Prakash & Khatod, 2016). The BESS further contributes to loss reduction by supplying power locally during peak demand periods (Abdullah et al., 2020).

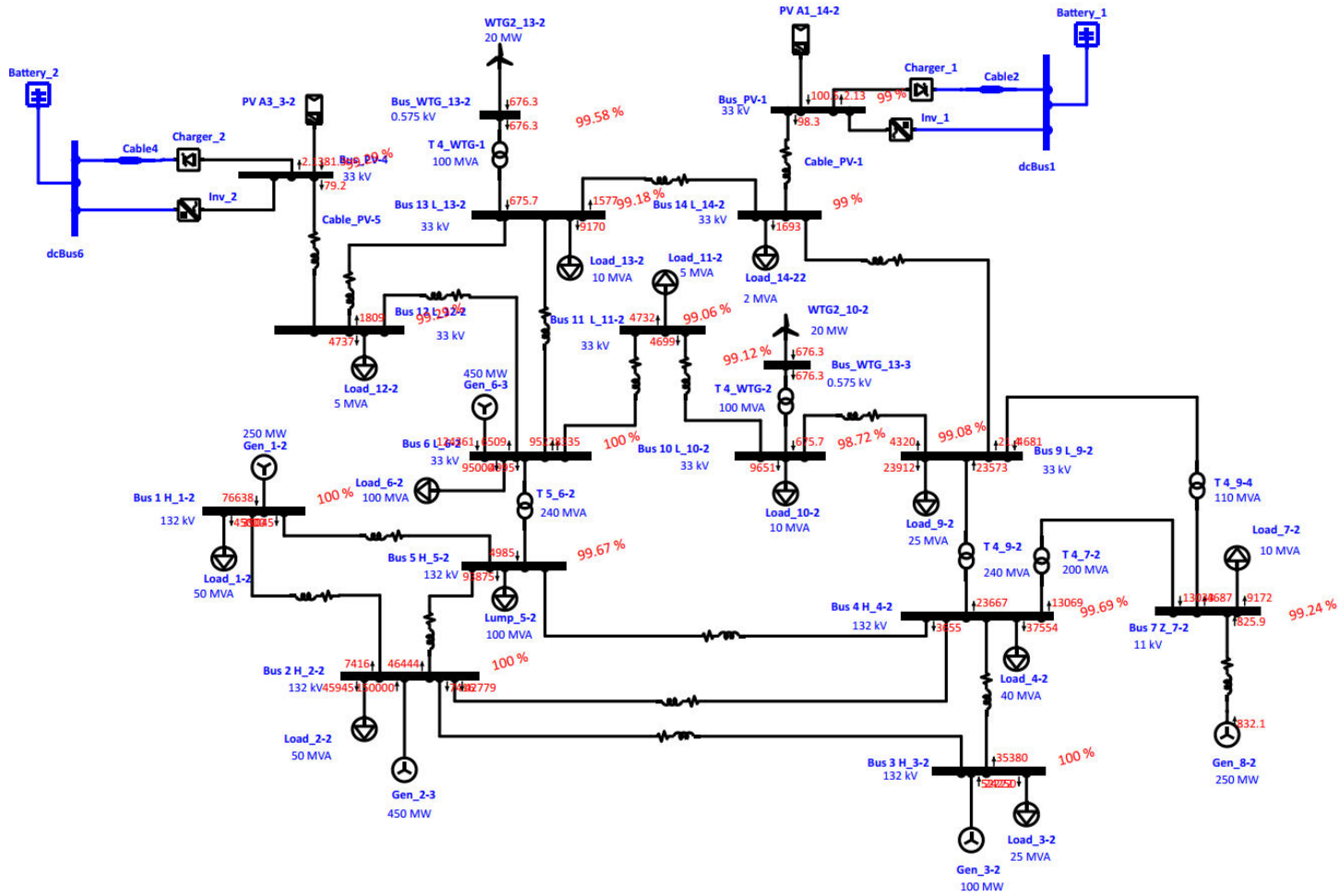


Figure 4.9: The simulated Solar PV-Wind-Battery HRES Grid-Tied System and Load Flow Analysis.

During these times, the electricity demand is high, which can strain the grid and lead to increased losses if power must be transmitted over long distances (Zhou et al., 2021). However, with BESS in place, power can be supplied locally from stored energy, reducing the need to draw power from distant sources (Abdullah et al., 2020). This localized supply not only reduces transmission losses but also eases the burden on the grid during peak periods, contributing to the overall stability and efficiency of the system (Abdullah et al., 2020; Kucevic et al., 2021; Zhou et al., 2021)

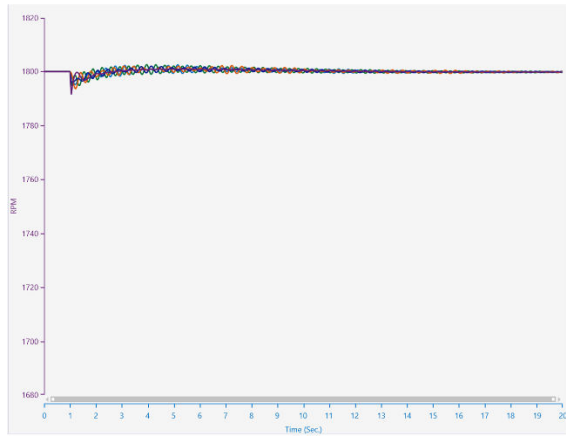
Generally, the integration of BESS into a Solar PV-Wind HRES provides significant benefits in terms of voltage stability and loss reduction. By maintaining stable voltage profiles and reducing line losses, BESS enhances the reliability and efficiency of the system, making it better suited to accommodate the variable nature of renewable energy sources. These findings align with existing literature, reinforcing the importance of BESS in modern energy systems, particularly as the share of renewable energy continues to grow.

#### **4.4.1. Transient stability analysis**

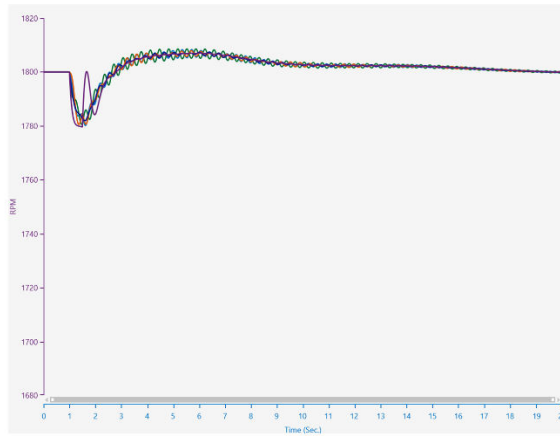
Transient stability analysis was similarly analyzed by simulating sudden disturbances in the system, i.e., faults.

##### **Fault on Buses**

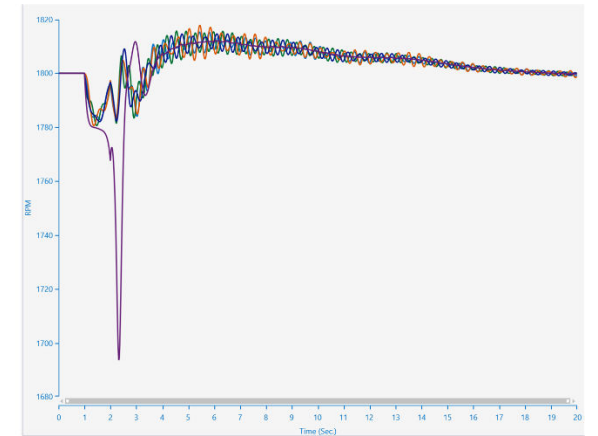
An LG fault was simulated on all the buses (one at a time) at 1.0 s and the fault was cleared at 1.05 s, 1.5 s, and 2.0 s. From the plots for the power angles and generator speeds against time in Figure 4.10. The results from the study highlight the dynamic behavior of the Solar PV-Wind HRES under fault conditions, with a focus on the  $V$  and  $f$  responses at different buses. The observed significant oscillations in the system immediately after a fault (oscillations when  $t_s$  was larger were greater compared to



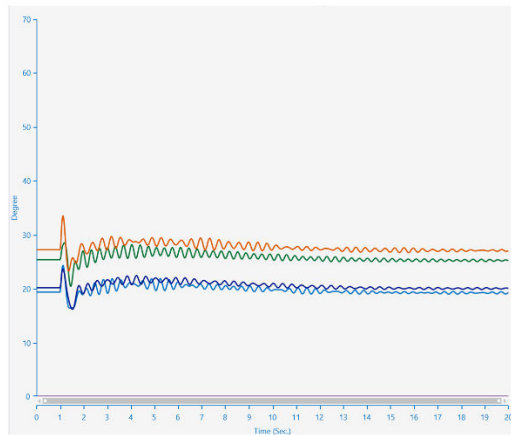
(a)



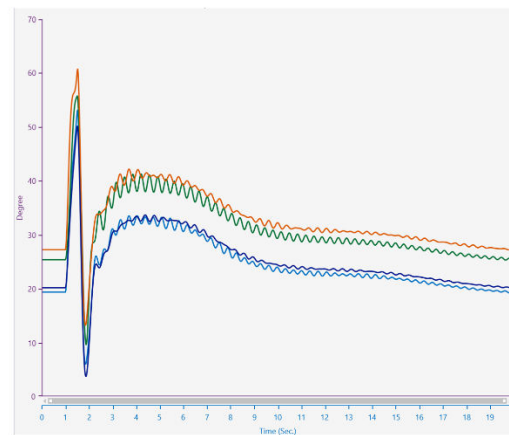
(b)



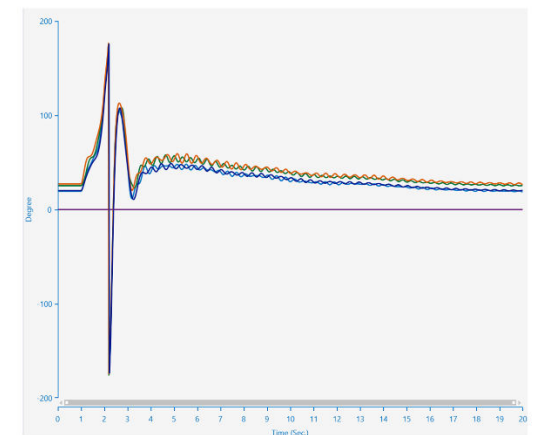
(c)



(d)



(e)



(f)

Figure 4.10: The plots for Power angle and Speed for the synchronous generators with a fault on Bus 5, (a) Speed at  $t_{ct} = 1.05$  s, (b) Speed at  $t_{ct} = 1.50$  s, (c) Speed at  $t_{ct} = 2.00$  s, (d) Power angle at  $t_{ct} = 1.05$  s, (e) Power angle at  $t_{ct} = 1.50$  s, (f) Power angle at  $t_{ct} = 2.00$  s.

when  $t_s$  is small) are consistent with the findings of Taul et al. (2019), who noted that such oscillations are a common transient response in power systems. These oscillations, while inherent in the system's reaction to disturbances, were found to be more pronounced when the  $t_s$  was longer. This suggests that the system's ability to stabilize post-fault is contingent on the duration of these oscillations, which can be influenced by various factors, including the system's configuration and the fault clearance time (Awelewa, 2016; Machowski et al., 2020). During the fault, the  $V$  and  $f$  at the bus where the fault occurred dropped sharply, as expected. This transient response is a typical indication of the system's inability to maintain stability during a fault (Bhui & Senroy, 2016). However, once the fault was cleared, both  $V$  and  $f$  recovered to their pre-fault levels, as shown in Figure 4.11, with the fault at Bus 5. This recovery process is crucial, as it demonstrates the system's resilience and ability to return to steady-state operation after a disturbance (Cassottana et al., 2019).

The analysis further revealed that the extent of  $V$  and  $f$  drops was directly related to the  $t_{ct}$ . Faster  $t_{ct}$  generally led to smaller deviations from the nominal values, which underscores the importance of quick fault detection and clearance mechanisms in maintaining system stability. Moreover, a comparative analysis between Solar PV-Wind HRES and Solar PV-Wind-Battery HRES with a fault at Bus 1 revealed a notable difference in the post-fault behavior. The Solar PV-Wind-Battery HRES system exhibited quicker damping of  $V$  oscillations compared to the Solar PV-Wind HRES system, as depicted in Figure 4.12. This indicates that the inclusion of a BESS in the hybrid system enhances the system's stability by providing additional support during and after the fault, thus reducing the severity and duration of oscillations (Hasan & Chowdhury, 2023).

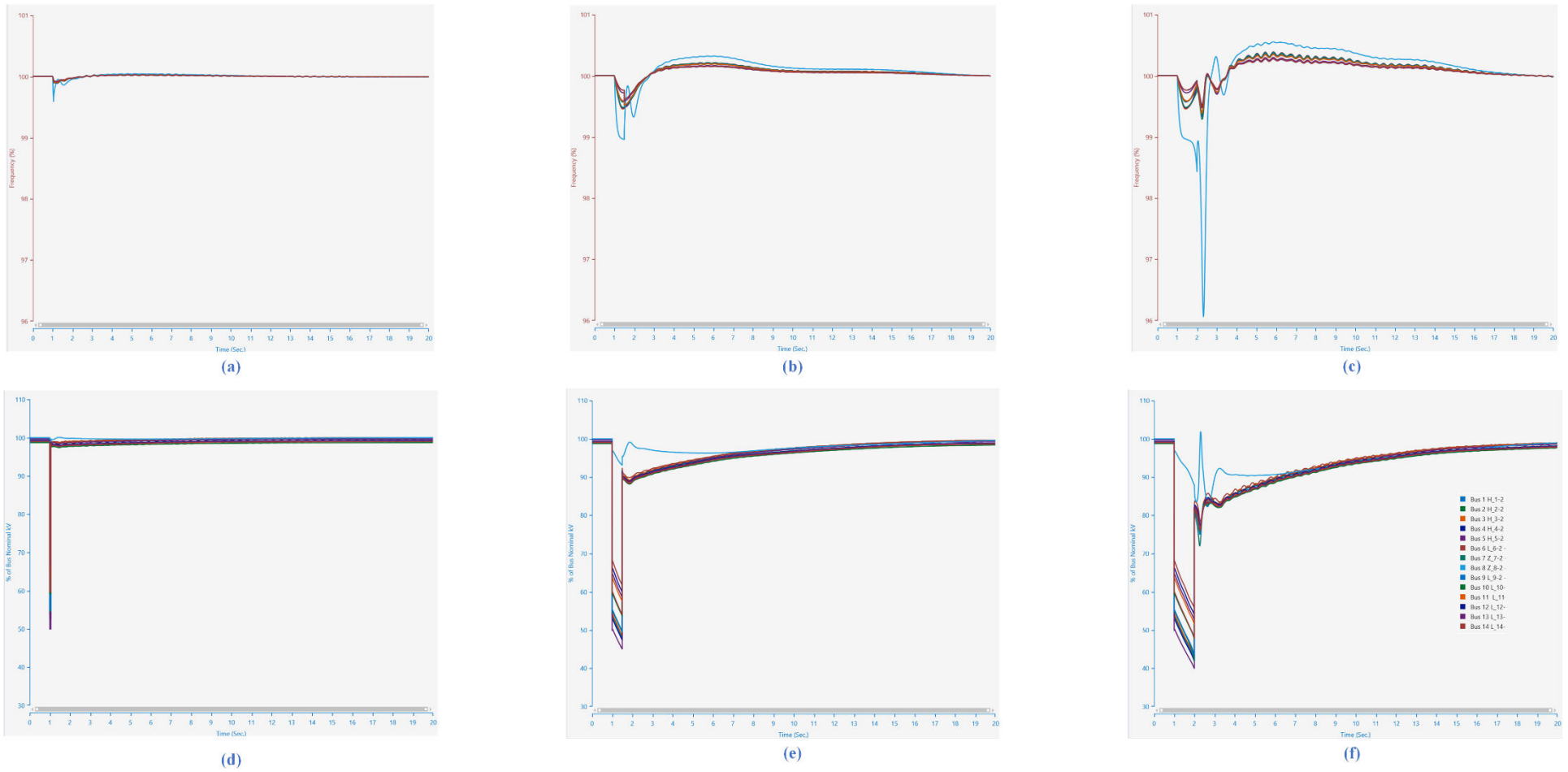


Figure 4.11: The plots for Frequency and Voltage for the synchronous generators with a fault on Bus 5, (a) Frequency at  $t_{ct} = 1.05$  s, (b) Frequency at  $t_{ct} = 1.50$  s, (c) Frequency at  $t_{ct} = 2.00$  s, (d) Voltage at  $t_{ct} = 1.05$  s, (e) Voltage at  $t_{ct} = 1.50$  s, (f) Voltage at  $t_{ct} = 2.00$  s

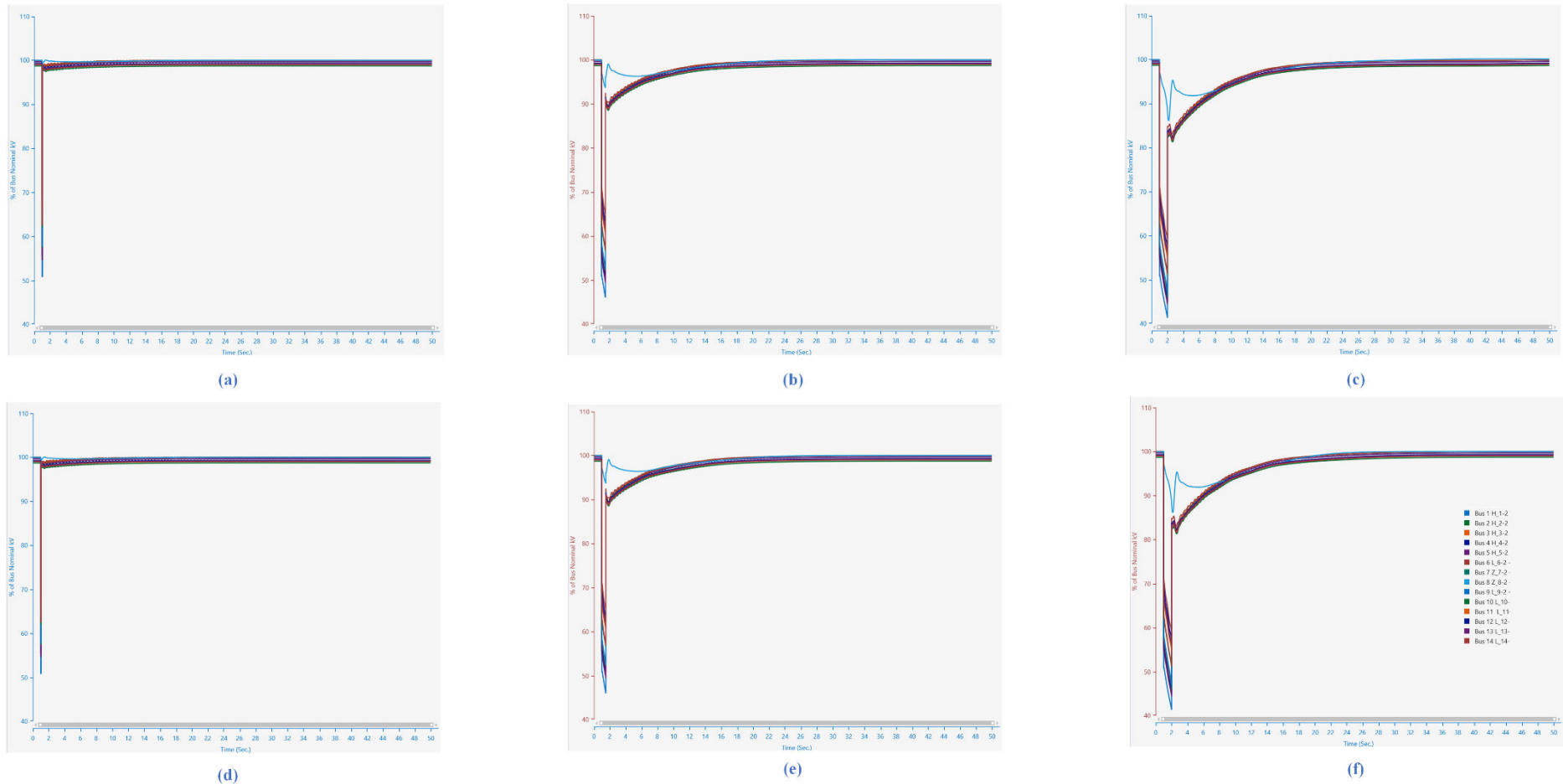


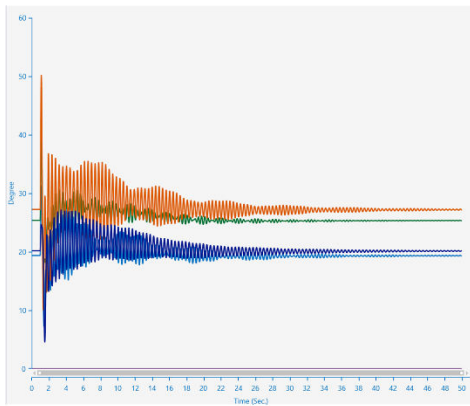
Figure 4.12: The differences in the Voltage profile for Solar PV-Wind HRES and Solar PV-Wind-Battery HRES, (a) Solar PV-Wind HRES at  $t_{ct} = 1.05$  s, (b) Solar PV-Wind HRES at  $t_{ct} = 1.50$  s, (c) Solar PV-Wind HRES at  $t_{ct} = 2.00$  s, (d) Solar PV-Wind-Battery HRES at  $t_{ct} = 1.05$  s, (e) Solar PV-Wind-Battery HRES at  $t_{ct} = 1.50$  s, (f) Solar PV-Wind-Battery HRES at  $t_{ct} = 2.00$  s.

These results highlight the critical role of  $t_{ct}$  and system configuration in determining the stability and resilience of HRES. The inclusion of a BESS in the HRES configuration appears to offer significant advantages in dampening post-fault oscillations, thereby enhancing overall system performance.

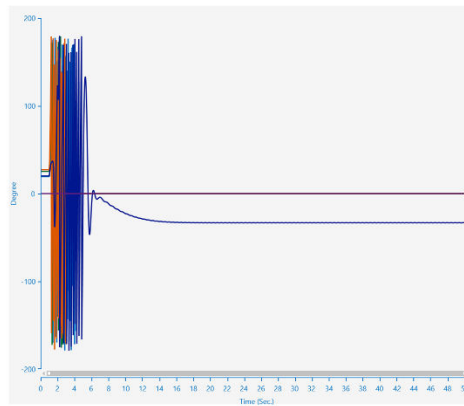
### **Fault on Transmission Lines**

Based on a similar analysis as the solar PV-Wind HRES system, Figure 4.13 presents the plots for the power angles and generator speeds against time at a  $F_p$  of 90% on fault at Line 5. In analyzing the transient stability of a Solar PV-Wind HRES connected to a grid, the study provides crucial insights into the impact of  $t_{ct}$  and  $F_p$  on system stability. Specifically, the observations at a  $t_{ct}$  of 1.05 s indicated that the system's oscillations dampened effectively, leading to stability for the connected generators. This implies that the generators could maintain synchronous operation, recovering from disturbances swiftly without losing synchronization, which is crucial for the continuous operation of the power system (Cheema, 2020). The dampening of oscillations is indicative of effective fault clearing within a time frame that allows the generators to stabilize (Xiong et al., 2020).

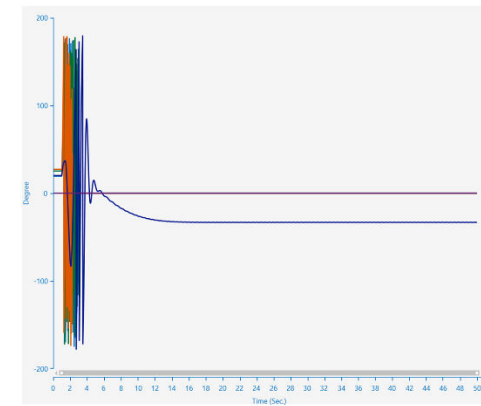
However, when the  $t_{ct}$  is extended beyond 1.50 s, the connected generators experience isolation, leading to a shutdown. This indicates that the  $t_{ct}$  is a critical parameter in ensuring system stability. If the fault persists too long, it can lead to a situation where the generators can no longer maintain synchronous operation, ultimately leading to their disconnection from the grid (Yaghobi, 2018). This shutdown scenario highlights the importance of prompt fault-clearing mechanisms to prevent widespread instability in the grid (Mastoi et al., 2023). The study further examines the impact of  $F_p$  on system stability, particularly focusing on  $f$  and  $V$  as key



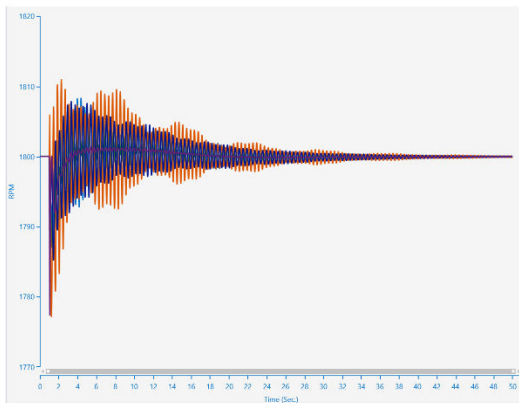
(a)



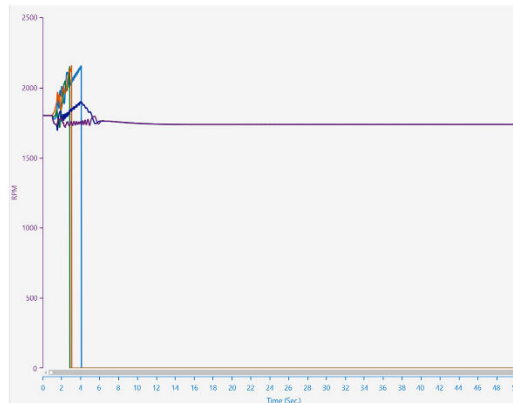
(b)



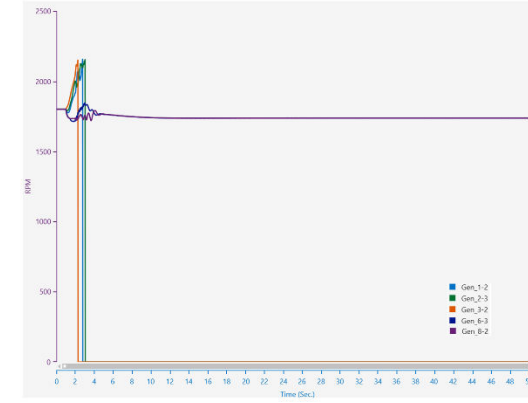
(c)



(d)



(e)



(f)

Figure 4.13: The plots for Power angle and Speed for the synchronous generators with a fault on transmission Line 4 at 90% fault position, (a) Power angle at  $t_{ct} = 1.05$  s, (b) Power angle at  $t_{ct} = 1.50$  s, (c) Power angle at  $t_{ct} = 2.00$  s, (d) Speed at  $t_{ct} = 1.05$  s, (e) Speed at  $t_{ct} = 1.50$  s, (f) Speed at  $t_{ct} = 2.00$  s

Indicators. From the results presented in Figures 4.14 and 4.15, it is observed that the impact of  $F_p$  at 100% is almost identical to that at 0%. This suggests that within the tested range,  $F_p$  variations do not significantly affect system stability. However, the deviation in system response is more pronounced with changes in  $t_{ct}$  than with changes in  $F_p$ . This highlights that while  $F_p$  is a factor in system stability, the timing of fault clearance plays a more crucial role.

These findings emphasize the critical role of  $t_{ct}$  in maintaining the stability of Solar PV-Wind-Battery HRES connected to the grid. Similarly, the ability of the system to stabilize after a disturbance is highly dependent on how quickly the fault is cleared, with longer delays leading to potential isolation and shutdown of generators. On the other hand,  $F_p$  levels, has a less significant impact on the overall system stability, making  $t_{ct}$  a more critical parameter to manage for ensuring the reliable operation of grid-tied HRES systems.

#### **4.4.2. Steady-state stability analysis**

The analysis aimed to evaluate the system's long-term operational stability with the HRES-integrated. The system was subjected to gradual load variations, both increases and decreases ( $\pm 2\%$  in solar PV and Wind generation), to assess its steady-state stability. The results indicated that the HRES effectively managed these variations, maintaining stable operation throughout the simulation.

The PV system's output adjusted according to the solar  $I_r$  levels, while the wind system responded to changes in  $S_w$ . As  $I_r$  levels increased, the PV system generated more power, contributing significantly to the overall energy output of the hybrid system. Conversely, during periods of low  $I_r$ , the PV system's contribution diminished, which was expected given the intermittent nature of solar energy (Notton

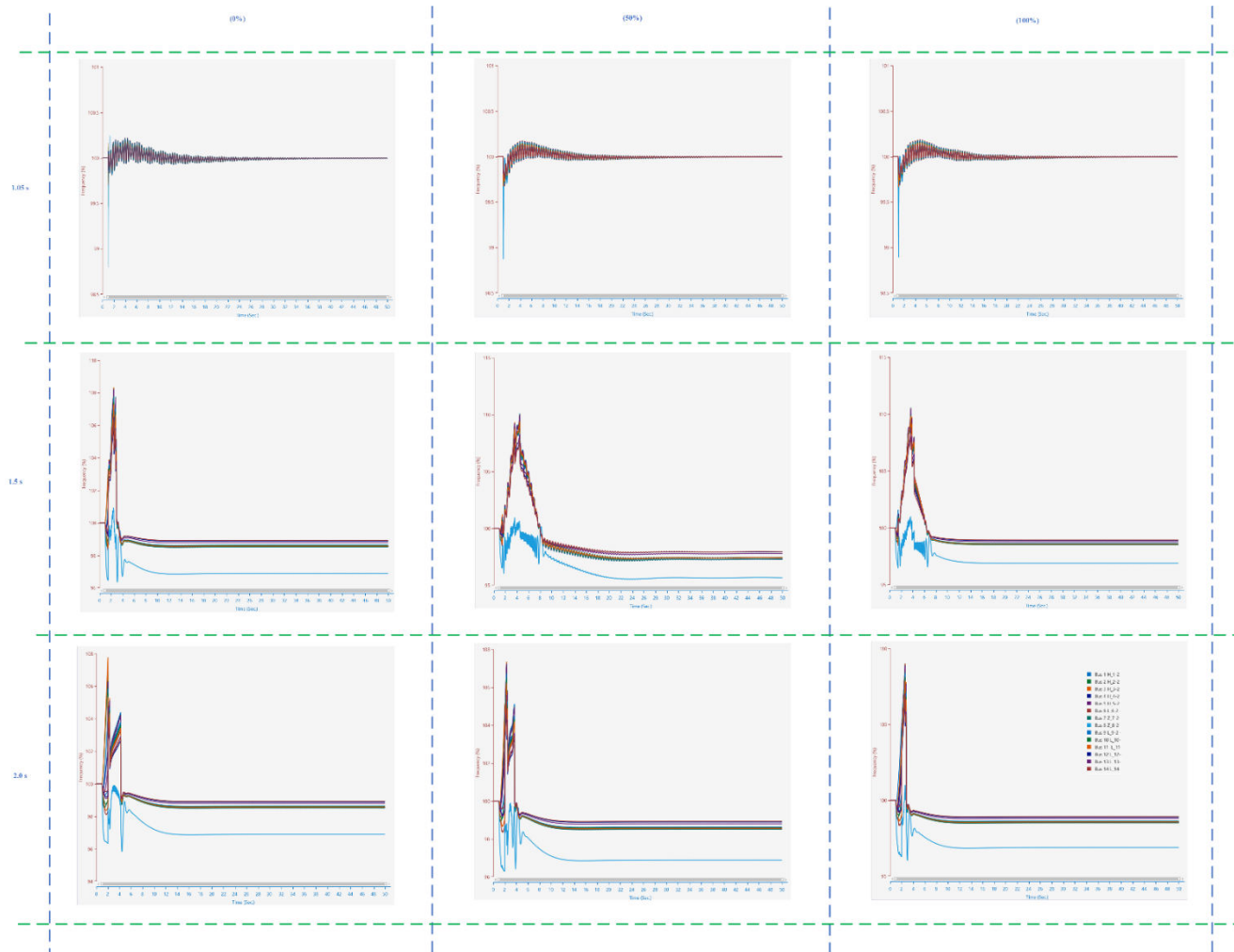


Figure 4.14: The plots for Frequency at different  $F_p$  and  $t_{ct}$

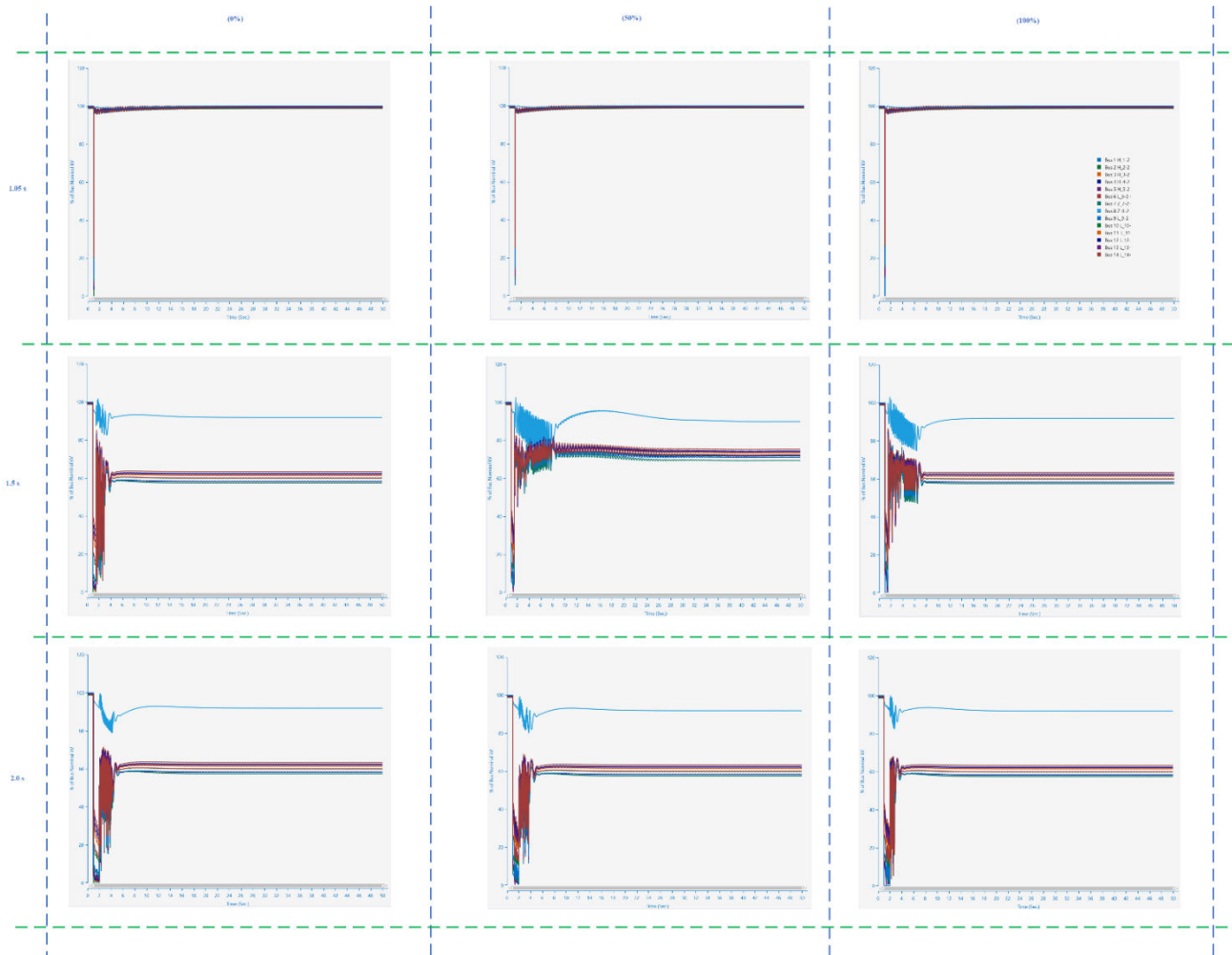


Figure 4.15: The plots for Voltage at different  $F_p$  and  $t_{ct}$ .

& Voyant, 2018). This variability underscores the need for complementary energy sources within hybrid systems to maintain a consistent power supply (McCormick & Suehrcke, 2018). Similarly, the wind energy system adjusted its output based on  $S_w$  variations. Wind energy is another renewable resource characterized by intermittency (Notton & Voyant, 2018). When  $S_w$  were high, the wind turbines generated more power, contributing to the system's energy mix. However, during periods of low  $S_w$ , the power output from the wind system decreased, necessitating support from other energy sources (Ren et al., 2017).

The BESS played a critical role in mitigating the effects of these fluctuations (Tantrapon et al., 2020). By charging during periods of low demand and discharging during periods of high demand, the battery system acted as a buffer, smoothing out the variability in power output from the PV and wind systems (Abdalla et al., 2023; Zhang et al., 2021). This capability is vital for maintaining a stable power supply, especially in hybrid systems that rely on variable renewable energy sources (Datta et al., 2021; Rana et al., 2022).

In terms of  $V$  stability, the simulation results indicated a significant improvement, particularly in buses that were previously identified as unstable as given in Table 4.6. The  $V$  stability margin was enhanced, reducing the risk of  $V$  collapse, which is crucial for the overall reliability of the power grid (Jalali & Aldeen, 2016). Additionally, the presence of the BESS contributed significantly to  $f$  stability. The battery's ability to respond rapidly to  $f$  deviations by injecting or absorbing power ensured that the system  $f$  remained within the acceptable range of 59.8 to 60.2 Hz, thereby preventing potential grid failures due to  $f$  instability (Mirsaeidi et al., 2017). Generally, the integration of BESS with PV and wind energy systems proved essential in enhancing both  $V$  and  $f$  stability, showcasing the potential of hybrid renewable energy systems in modern power grids.

Table 4.6: The Voltage Stability Index (VSI) for each bus

<b>Bus</b>	<b>Voltage Stability Index (VSI)</b>
Bus 1	0.12
Bus 2	0.11
Bus 3	0.13
Bus 4	0.12
Bus 5	0.15
Bus 6	0.11
Bus 7	0.19
Bus 8	0.14
Bus 9	0.24
Bus 10	0.31
Bus 11	0.34
Bus 12	0.29
Bus 13	0.31
Bus 14	0.32

Lastly, Eigenvalue analysis was performed to assess the system's dynamic stability. The eigenvalues of the system's state matrix were computed, and their real parts were observed.

The results indicated that all eigenvalues had negative real parts (Figure 4.8), which is a strong indicator that the system is stable in its steady-state operation (Brunetti et al., 2016). This result suggests that the system will return to its equilibrium point after a disturbance, without any oscillatory or unstable behavior (Brunetti et al., 2016)

Furthermore, the integration of the BESS into the system did not introduce any new instability modes. This finding is significant as it demonstrates that the addition of BESS does not negatively affect the system's dynamic performance. The system minimum damping improved to 0.29 towards the critical damping condition of 1. The damping ratio indicates how quickly oscillations decay after a disturbance, and a ratio of 0.29 suggests adequate damping, ensuring the system's stability without excessive oscillations (Zhang et al., 2016). The results of the eigenvalue analysis confirm that the integration of BESS into the system is feasible from a stability perspective. The system remains stable, and its dynamic behavior is well-damped.

Table 4.7: The descriptive statistics of the setting time for generator speed bus frequency and bus voltage with BESS( $n = 4060$ ).

<b>Descriptive statistics</b>	<b>Speed (s)</b>	<b>Frequency (s)</b>	<b>Voltage (s)</b>
Maximum	50.000	49.981	50.000
Minimum	1.021	1.050	1.021
Range	48.979	48.931	48.979
Interquartile Range	19.15	6.72	16.96
Median	6.206	4.691	5.781
Skewness	1.138	3.000	1.291
Mean	15.513	6.793	14.875
Standard error	0.281	0.125	0.268
Standard deviation	17.936	7.962	17.075
Variance	321.716	63.394	291.557

#### 4.4.3. Quantitative analysis

A descriptive statistic of the entire data is given in Table 4.7 in terms of measures of central tendency and measures of variability (spread) in  $t_s$  for  $G_s$ ,  $V$ , and  $f$ . It was

established that the mean  $t_s$  for  $G_s$  was 15.513 s with a median of 6.206 s ranging from 1.021 s (minimum) to 50.000 s (maximum). The mean  $t_s$  for  $f$  was 6.793 s with a median of 4.691 s ranging from 1.050 s (minimum) to 49.981 s (maximum). Lastly, the mean  $t_s$  for  $V$  was 14.875 s with a median of 5.781 s ranging from 1.021 s (minimum) to 50.000 s (maximum). Similarly, a Log transformation was performed on the data, and the transformed data normality was ascertained by the Shapiro-Wilk Test.

### **Fault on buses**

For each variable, i.e.,  $f$ ,  $V$ , and  $G_s$ , the  $t_s$  was analyzed as presented in Table 4.8. Firstly, a two-way ANOVA was conducted that examined the effect of  $t_{ct}$  and  $B$  on  $t_s$  of a Solar-PV-Wind-Battery HRES Grid-tied to an IEEE 14 bus system based on  $f$ . There was a statistically significant interaction between the effects of  $t_{ct}$  and  $B$  on the  $t_s$  of ( $p < 0.05$ ). Indicating that the combined effect of these variables significantly influences the system's  $t_s$  after a disturbance, while the relationship between  $t_{ct}$  and the  $B$  impact is not straightforward and depends on the interaction between these factors. However, there was no statistically significant difference in the  $B$  on the  $t_s$  of ( $p < 0.05$ ). This indicates that the battery's presence did not independently affect the  $t_s$  for frequency, highlighting that other system parameters or the interaction with  $t_{ct}$  might play more crucial roles in this context. Additionally, there was a statistically significant difference in the  $t_{ct}$  on the  $t_s$  of ( $p < 0.05$ ), with  $t_{ct} = 2.00$  s having a significantly higher  $t_s$  than all the other  $t_{ct}$ . Similarly, this finding underscores the critical importance of fault clearance time in determining the system's frequency stability. A longer  $t_{ct} = 2.00$  s led to a slower return to a steady state, which could imply greater system instability or longer periods of oscillations

following a disturbance. This emphasizes the need for rapid fault clearance to enhance system performance.

Table 4.8: The statistical results of the settling time ( $t_s$ ) expressed in terms of mean and standard deviation with BESS

Fault clearance time ( $t_{ct}$ )	$f(t_s)$	$V(t_s)$	$G_s(t_s)$
$t_{ct} = 1.05\text{ s}$	$5.284 \pm 0.421$	$9.568 \pm 0.521^a$	$10.129 \pm 0.529^a$
$t_{ct} = 1.50\text{ s}$	$5.113 \pm 0.486$	$10.045 \pm 0.433^a$	$10.991 \pm 0.634^a$
$t_{ct} = 2.00\text{ s}$	$6.069 \pm 0.558$	$12.921 \pm 0.507^b$	$11.621 \pm 0.607^b$

a, b mean  $\pm$  std within a column with no superscript in common differ significantly ( $p < 0.05$ )

Secondly, a two-way ANOVA was conducted that examined the effect of  $t_{ct}$  and  $B$  on the  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $G_s$ . There was a statistically significant interaction between the effects of  $t_{ct}$  and  $B$  on the  $t_s$  of  $G_s$  ( $p < 0.05$ ). A simple main effects analysis showed that  $t_{ct} = 2.00\text{ s}$  had a significantly higher  $t_s$  than  $t_{ct} = 1.05\text{ s}$  and  $t_{ct} = 1.50\text{ s}$ . Furthermore, there were statistically significant differences between  $t_{ct} = 1.05\text{ s}$  and  $t_{ct} = 2.00\text{ s}$ , while there were no statistically significant differences between  $t_{ct} = 1.05\text{ s}$  and  $t_{ct} = 1.50\text{ s}$ .

Lastly, a two-way ANOVA was conducted that examined the effect of  $t_{ct}$  and  $B$  on the  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $V$ . There was a statistically significant interaction between the effects of  $t_{ct}$  and  $B$  on the  $t_s$  of ( $p < 0.05$ ). This further reinforces the idea that the combined effects of these variables are crucial in determining the system's dynamic response to faults. A simple main effects analysis showed that  $t_{ct} = 2.00\text{ s}$  had a significantly higher  $t_s$  than  $t_{ct} = 1.05\text{ s}$  and  $t_{ct} = 1.50\text{ s}$ . This indicates that longer  $t_{ct}$  consistently lead to poorer system performance, not only in terms of  $f$  but also  $V$  and  $G_s$  stability. Additionally, there were statistically significant differences between  $t_{ct} = 1.05\text{ s}$  and

$t_{ct} = 2.00$  s, while there were no statistically significant differences between  $t_{ct} = 1.05$  s and  $t_{ct} = 1.50$  s. This suggests that a  $t_{ct}$  of around 1.50 s is an optimal threshold for maintaining both  $f$  and  $V$  and  $G_s$  stability without significantly degrading system performance.

Table 4.9: A summary of the data on the effect of fault position ( $F_p$ ) and fault clearance time ( $t_{ct}$ ) on settling time ( $t_s$ ) for Frequency ( $f$ ), voltage ( $V$ ) and generator speed ( $G_s$ ) (with BESS)

$F_p$	$t_{ct}$	$f(t_s)$	$V(t_s)$	$G_s(t_s)$
0% mean $\pm$ std	$t_{ct} = 1.05$ s	2.999 $\pm$ 0.357	6.152 $\pm$ 0.418	3.529 $\pm$ 0.385
	$t_{ct} = 1.50$ s	7.165 $\pm$ 0.262	13.728 $\pm$ 0.315	7.136 $\pm$ 0.304
	$t_{ct} = 2.00$ s	12.565 $\pm$ 0.524	23.688 $\pm$ 0.397	18.435 $\pm$ 0.477
10% mean $\pm$ std	$t_{ct} = 1.05$ s	1.3066 $\pm$ 0.104	2.533 $\pm$ 0.242	1.453 $\pm$ 0.127
	$t_{ct} = 1.50$ s	6.603 $\pm$ 0.164	17.090 $\pm$ 0.364	11.957 $\pm$ 0.385
	$t_{ct} = 2.00$ s	14.668 $\pm$ 0.309	34.763 $\pm$ 0.425	27.160 $\pm$ 0.487
25% mean $\pm$ std	$t_{ct} = 1.05$ s	1.313 $\pm$ 0.108	2.545 $\pm$ 0.241	1.427 $\pm$ 0.122
	$t_{ct} = 1.50$ s	7.964 $\pm$ 0.234	15.239 $\pm$ 0.349	10.009 $\pm$ 0.336
	$t_{ct} = 2.00$ s	15.043 $\pm$ 0.369	29.321 $\pm$ 0.488	23.963 $\pm$ 0.530
50% mean $\pm$ std	$t_{ct} = 1.05$ s	1.376 $\pm$ 0.123	2.599 $\pm$ 0.246	1.467 $\pm$ 0.133
	$t_{ct} = 1.50$ s	6.591 $\pm$ 0.149	14.497 $\pm$ 0.317	9.548 $\pm$ 0.338
	$t_{ct} = 2.00$ s	12.631 $\pm$ 0.278	31.580 $\pm$ 0.401	24.962 $\pm$ 0.503
75% mean $\pm$ std	$t_{ct} = 1.05$ s	1.384 $\pm$ 0.117	2.709 $\pm$ 0.258	1.496 $\pm$ 0.129
	$t_{ct} = 1.50$ s	5.553 $\pm$ 0.163	10.551 $\pm$ 0.294	6.423 $\pm$ 0.232
	$t_{ct} = 2.00$ s	12.328 $\pm$ 0.276	28.738 $\pm$ 0.398	22.354 $\pm$ 0.497
90% mean $\pm$ std	$t_{ct} = 1.05$ s	1.600 $\pm$ 0.174	2.965 $\pm$ 0.261	1.729 $\pm$ 0.175
	$t_{ct} = 1.50$ s	5.697 $\pm$ 0.195	10.945 $\pm$ 0.356	6.225 $\pm$ 0.266
	$t_{ct} = 2.00$ s	8.653 $\pm$ 0.200	23.926 $\pm$ 0.406	19.434 $\pm$ 0.479
100% mean $\pm$ std	$t_{ct} = 1.05$ s	1.223 $\pm$ 0.093	3.020 $\pm$ 0.289	1.622 $\pm$ 0.193
	$t_{ct} = 1.50$ s	7.913 $\pm$ 0.246	14.075 $\pm$ 0.349	9.822 $\pm$ 0.343
	$t_{ct} = 2.00$ s	8.431 $\pm$ 0.334	22.970 $\pm$ 0.472	16.625 $\pm$ 0.527

### Fault on Transmission Lines

A summary of the data is given in Table 4.9. it was observed that the  $t_s$  for  $t_{ct} = 2.00$  s was still much higher than that of  $t_{ct} = 1.05$  s and  $t_{ct} = 1.50$  s. For each variable, i.e.,  $f$ ,  $V$ , and  $G_s$ , the  $t_s$  was analyzed to determine the effects of  $t_{ct}$ ,  $F_p$ , and  $B$  as presented in Table 4.10. Firstly, a three-way ANOVA was conducted that examined the effect of  $t_{ct}$ ,  $F_p$ , and  $B$  on  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an

IEEE 14 bus system based on  $V$ . There was a statistically significant three-way interaction between  $t_{ct}$ ,  $F_p$ , and  $B$  ( $p < 0.05$ ). This implies that the relationship between any two of the variables ( $t_{ct}$ ,  $F_p$ , and  $B$ ) on the  $t_s$  is not consistent across the levels of the third variable. In other words, the influence of  $t_{ct}$  on the  $t_s$  depends on both the  $F_p$  and the presence of a  $B$ . This significant interaction indicates that the system's  $V$  response is highly sensitive to the specific conditions of  $t_{ct}$ ,  $F_p$ , and  $B$  status. It suggests that optimizing these parameters simultaneously is crucial for maintaining voltage stability in the grid-tied system.

Secondly, a three-way ANOVA was conducted that examined the effect of  $t_{ct}$ ,  $F_p$ , and  $B$  on  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $f$ . It was established that there was a statistically significant three-way interaction between  $t_{ct}$ ,  $F_p$ , and  $B$  ( $p < 0.05$ ). This finding aligns with the results obtained for  $V$ , underscoring the complexity of the system's dynamic behavior. The  $f$  of the system is a critical parameter in grid stability, and the significant interaction effect suggests that deviations in the  $t_s$  of  $f$  are influenced by the interplay of  $t_{ct}$ ,  $F_p$ , and the presence of a  $B$ . The significant interaction reveals that these factors cannot be considered in isolation when designing or analyzing the system, as their combined effect can lead to variations in the system's ability to return to its nominal  $f$  after disturbances.

Lastly, a three-way ANOVA was conducted that examined the effect of  $t_{ct}$ ,  $F_p$ , and  $B$  on  $t_s$  of a Solar-PV-Wind HRES Grid-tied to an IEEE 14 bus system based on  $G_s$ . There was no statistically significant three-way interaction between  $t_{ct}$ ,  $F_p$ , and  $B$  ( $p < 0.05$ ).

Table 4.10: The statistical results of the settling time ( $t_s$ ) expressed in terms of mean and standard deviation (with BESS)

Fault position ( $F_p$ )	$f(t_s)$	$V(t_s)$	$G_s(t_s)$
0% mean $\pm$ std	7.576 $\pm$ 0.468 <sup>g</sup>	14.523 $\pm$ 0.492 <sup>ae</sup>	9.700 $\pm$ 0.519 <sup>ab</sup>
10% mean $\pm$ std	7.526 $\pm$ 0.451 <sup>afg</sup>	18.129 $\pm$ 0.566 <sup>ad</sup>	13.523 $\pm$ 0.582 <sup>a</sup>
25% mean $\pm$ std	7.937 $\pm$ 0.473 <sup>dfg</sup>	15.369 $\pm$ 0.544 <sup>aceg</sup>	12.053 $\pm$ 0.556 <sup>ab</sup>
50% mean $\pm$ std	6.866 $\pm$ 0.422 <sup>achfg</sup>	16.225 $\pm$ 0.532 <sup>af</sup>	12.052 $\pm$ 0.558 <sup>b</sup>
75% mean $\pm$ std	6.465 $\pm$ 0.423 <sup>aeg</sup>	14.172 $\pm$ 0.514 <sup>efh</sup>	10.091 $\pm$ 0.513 <sup>b</sup>
90% mean $\pm$ std	5.317 $\pm$ 0.359 <sup>b</sup>	12.612 $\pm$ 0.479 <sup>ch</sup>	9.129 $\pm$ 0.480 <sup>b</sup>
100% mean $\pm$ std	5.740 $\pm$ 0.429 <sup>beh</sup>	13.097 $\pm$ 0.495 <sup>bgh</sup>	9.179 $\pm$ 0.508 <sup>b</sup>

a, b mean  $\pm$  std within a column with no superscript in common differ significantly ( $p < 0.05$ )

This result indicates that the  $t_s$  of  $G_s$  is not significantly affected by the combined interaction of  $t_{ct}$ ,  $F_p$ , and  $B$  status. This lack of interaction might imply that  $G_s$ , unlike  $V$  and  $f$ , is less sensitive to the simultaneous variations in these parameters or that the system's design inherently stabilizes generator speed more effectively under varying conditions of  $t_{ct}$ ,  $F_p$ , and  $B$ . Therefore, in terms of  $G_s$ , the factors may act more independently, with no substantial combined effect on the  $t_s$ .

### Effect of Battery Energy Storage System

To evaluate the effect of the Battery on the entire system an independent t-test was performed as given in Table 4.11.

Table 4.11: The results for the independent t-test in terms of mean and standard deviation

System	$f(\text{mean} \pm \text{std})$	$V(\text{mean} \pm \text{std})$	$G_s(\text{mean} \pm \text{std})$
PV-Wind	15.843 $\pm$ 0.594 <sup>a</sup>	14.825 $\pm$ 0.524	10.473 $\pm$ 0.543298
PV-Wind Battery	6.781 $\pm$ 0.434 <sup>b</sup>	14.891 $\pm$ 0.519	10.815 $\pm$ 0.532010

a,b mean  $\pm$  std within a column, with no superscript in common, differ significantly ( $p < 0.05$ )

The independent t-test established that there was no statistically significant difference between the PV-Wind Battery Hybrid system and the PV-Wind Hybrid system in terms of  $t_s$  of  $V$  ( $p < 0.05$ ). Additionally, there was no statistically significant difference between the PV-Wind Battery Hybrid system and the PV-Wind Hybrid

system in terms of  $t_s$  of  $G_s$  ( $p < 0.05$ ). These results indicate that the BESS does not significantly alter the system's  $V$  and  $G_s$  stability under the conditions tested. These parameters are crucial for maintaining system reliability, and the findings suggest that the hybrid system's overall stability in these aspects is not heavily dependent on the presence of a BESS. However, the PV-Wind Battery Hybrid system had a statistically significantly lower  $t_s$  of  $f$  compared to the PV-Wind Hybrid system ( $p < 0.05$ ). This highlights the battery's critical role in improving  $f$  stability.  $f$  stability is vital for the synchronous operation of power systems, and the ability of the BESS to enhance this aspect suggests that it effectively compensates for the inherent variability of renewable energy sources like wind and solar (Datta, 2020). The BESS likely provides rapid frequency support during fluctuations, which is particularly beneficial during events of sudden load changes or renewable output variations (Datta, 2020; Karbouj et al., 2019).

Moreover, the general impact of the BESS on both transient and steady-state stability cannot be overlooked. In transient conditions, the BESS contributes by providing immediate power support, which is crucial for stabilizing rotor angles and aiding in the quick recovery of system voltages following disturbances (Gu, 2023). This function is particularly valuable in preventing cascading failures and ensuring system robustness in the face of short-term disruptions (Gu, 2023). In steady-state conditions, the BESS plays a role in smoothing power fluctuations and maintaining stable bus voltages, which is essential for mitigating the variability associated with renewable energy sources (Datta, 2020).

## CHAPTER FIVE

### CONCLUSIONS AND RECOMMENDATIONS

#### 5.1. Conclusion

The increasing global reliance on renewable energy sources, particularly solar PV and wind energy has necessitated the development of hybrid systems that can harness the strengths of both technologies. Hybrid solar PV-wind grid-tie systems offer a promising solution to the challenges of renewable energy integration, providing enhanced reliability, efficiency, and stability. However, the dynamic nature of these systems, influenced by fluctuating weather conditions and varying load demands, makes stability analysis a critical area of study. This research focused on the transient and steady-state stability analysis of a solar PV-wind grid-tie hybrid system, to understand the system's behavior under different operating conditions and identify strategies to enhance its stability.

The first objective of this study was to develop a detailed and accurate simulation of an IEEE 14 Bus system and integrate the solar PV and wind renewable energy systems. The load flow analysis of the IEEE 14 Bus system established that direct connection between the generator and buses results in higher voltage levels, as there is less impedance and fewer losses between the generator and these buses. The bus voltages ranged from 0.9832 p.u. to 1.00 p.u. Additionally, the Load Flow analysis aimed to identify the optimal buses for the integration of Solar PV and Wind resources by focusing on those that are furthest from the generator yet exhibit stable voltage profiles. This strategy is beneficial as it supports the distributed generation model, enhances voltage stability, reduces transmission losses, and improves overall grid efficiency. Therefore, by carefully selecting the buses for renewable integration, the

power system can accommodate clean energy sources while maintaining stability and reliability, which are crucial for the sustainable development of the grid.

The second objective was to analyze the transient stability of the hybrid grid-tie system under sudden changes, i.e., faults on transmission lines and buses. The integration of PV and wind systems into the IEEE 14-bus system does result in some variations in voltage and changes in power flow patterns, i.e., 0.9929 p.u. to 0.99 p.u. for buses connected to the PV system and 0.9878 p.u. to 0.9918 p.u. for buses connected to the wind system. Therefore, these changes are manageable and do not compromise the overall stability of the system. Additionally, the integration of renewable energy sources into the power grid does introduce additional reactive power flows leading to a slight increase in system losses (about 0.02%), the impact is minimal and does not significantly affect system efficiency. When the fault occurred on the buses both voltage, frequency, and generator speed experienced a significant drop but showed a notable recovery to pre-fault levels once the fault was cleared. However, the level of voltage and frequency drops were directly proportional to  $t_{ct}$ . However, when the fault occurs on the transmission line as the fault clearance time increases (greater than 1.05 s) the generators connected to the faulted line will be isolated. Additionally, fault position doesn't have much effect on the voltage and frequency profiles, however, the fault clearance time had a noticeable effect. i.e., the settling time for the fault clearance time of 1.50 s and 2.00 s were longer compared to those of 1.05 s. Moreover, in the analysis of  $t_{ct}$  and  $t_s$  for voltage, frequency, and generator speed, shorter  $t_{ct}$  values consistently led to faster stabilization times, which is advantageous for maintaining system stability during transient disturbances.

The third objective was to analyze the steady-state stability of the hybrid grid-tie system in response to small, continuous changes in operating conditions, i.e., gradual

variations in solar irradiance and wind speed. Despite the variations in generation ( $\pm 20\%$  due to changes in irradiance, and  $\pm 15\%$  due to wind speed changes), the system remained stable, with no significant voltage or frequency deviations observed. Additionally, the eigenvalue analysis ascertained the stability of the system under gradual changes by all eigenvalues being located in the left half of the complex plane. Furthermore, the system had a minimum damping ratio of 0.15. Hence, any oscillations following small disturbances were quickly dampened. Moreover, in the analysis of  $t_{ct}$ ,  $F_p$ , and  $t_s$  for voltage, frequency, and generator speed, The system's transient stability was highly affected by the  $t_{ct}$  and the level of  $F_p$ .

The fourth objective was to determine the impact of energy storage systems on the stability and reliability of hybrid grid-tie systems. The integration of BESS into a Solar PV-Wind hybrid energy system provided significant benefits in terms of voltage stability (0.98772 to 1.000 p.u.) and loss reduction (1.25%). The BESS enhances the reliability and efficiency of the system by maintaining stable voltage profiles and reducing line losses, making it better suited to accommodate the variable nature of renewable energy sources.

Generally, the study was structured to address key aspects of Solar PV-Wind HRES system stability, including the development of a comprehensive system model, the application of advanced simulation tools, Load Flow analysis, and the analysis of both transient and steady-state stability. The transient stability analysis involved examining the system's response to sudden disturbances, i.e., faults, while the steady-state stability analysis focused on the system's ability to maintain equilibrium under normal operating conditions. The load flow analysis established that while the integration of PV and wind systems into the IEEE 14-bus system does result in some variations in

voltage and changes in power flow patterns (0.9878 – 0.9999 p.u.), these changes are manageable and do not compromise the overall stability of the system. The findings highlight the importance of careful planning and analysis when integrating renewable energy sources into existing power grids, as well as the potential benefits in terms of improved voltage profiles and enhanced system stability.

The results of the transient stability analysis revealed that the hybrid system's response to disturbances is highly dependent on the balance between solar PV and wind energy contributions. In scenarios where one energy source dominates, the system is more vulnerable to instability, particularly during periods of low inertia or high variability in generation. For instance, during low wind conditions, the solar PV system needs to compensate by providing more power, but this can lead to voltage fluctuations and increased susceptibility to faults. Conversely, in high wind conditions, the rapid changes in wind speed can cause frequency deviations, which the solar PV system may not be able to stabilize effectively. The steady-state stability analysis provided insights into the hybrid system's long-term performance. It was observed that the system's ability to maintain voltage and frequency stability is influenced by the configuration of the grid-tie inverter, the quality of the power electronics, and the system's overall design. Moreover, the study found that the integration of energy storage systems, such as batteries, can significantly enhance steady-state stability by providing a buffer against fluctuations and allowing for smoother transitions between different operating states. While the integration of renewable energy sources into the power grid does introduce additional reactive power flows leading to a slight increase in system losses (0.002%), the impact is minimal and does not significantly affect system efficiency. The continued improvement in control strategies and grid management techniques will likely further mitigate these losses, making HRES a

viable and efficient solution for the future energy landscape. The  $t_{ct}$  is a critical factor in determining the stability of generators in a grid-tied system. While a  $t_{ct}$  of 1.05 s is effective in damping oscillations and maintaining stability, any delay beyond this threshold can lead to significant instability, culminating in the isolation of generators from the grid. While  $F_p$  appears to have a limited effect on voltage and frequency stability,  $t_{ct}$  is a critical factor influencing the system's  $t_s$  and overall stability. The results emphasize the need for efficient fault management strategies to enhance system resilience and stability. A key finding from the comparison of transient and steady-state stability analyses is the complementary nature of these two aspects of stability. While transient stability is crucial for ensuring that the system can withstand sudden disturbances, steady-state stability is essential for the system's reliable operation over time. The research highlighted the importance of a holistic approach to stability analysis, where both transient and steady-state factors are considered in the design and operation of hybrid solar PV-Wind systems.

The results of the quantitative analysis of the  $t_s$  of SolarPV-Wind HRES analyses indicate a clear relationship between  $t_{ct}$  and the stabilization times of  $V$ ,  $f$ , and  $G_s$  in a Solar-PV-Wind HRES grid-tied to an IEEE 14 bus system. Across all three parameters, shorter  $t_{ct}$  values consistently led to faster stabilization times, which is advantageous for maintaining system stability during transient disturbances. The lack of significant differences between  $t_{ct} = 1.50$  s and  $t_{ct} = 2.00$  s suggests that while extending  $t_{ct}$  beyond 1.50 s may not yield further benefits in stabilization time, reducing  $t_{ct}$  below this threshold is critical for optimal system performance. These findings highlight the importance of carefully selecting  $t_{ct}$  to ensure both the reliability and efficiency of hybrid renewable energy systems connected to the grid. Additionally, it was established that  $F_p$  also affect the transient stability of a Solar-

PV-Wind HRES Grid-tied to an IEEE 14-bus system, however  $t_{ct}$  has a greater impact on stability.

The integration of BESS into a Solar PV-Wind HRES provides significant benefits in terms of voltage stability and loss reduction. By maintaining stable voltage profiles and reducing line losses, BESS enhances the reliability and efficiency of the system, making it better suited to accommodate the variable nature of renewable energy sources. Based on a comparative analysis, integrating battery storage in HRES leads to improved performance in fault scenarios and overall system stability. Similarly,  $t_{ct}$  plays a critical role in determining the stability and resilience of Solar PV-Wind HRES. Despite the inclusion of a BESS in the HRES configuration offers significant advantages in dampening post-fault oscillations, thereby enhancing overall system performance. Nevertheless, the findings emphasize the critical role of  $t_{ct}$  in maintaining the stability of Solar PV-Wind-Battery HRES connected to the grid. The ability of the system to stabilize after a disturbance is highly dependent on how quickly the fault is cleared, with longer delays leading to potential isolation and shutdown of generators. On the other hand,  $F_p$ , within the tested limits, has a less significant impact on the overall system stability, making  $t_{ct}$  a more critical parameter to manage for ensuring the reliable operation of grid-tied HRES systems. Additionally, the eigenvalue analysis confirms that the integration of BESS into the system is feasible from a stability perspective as the system is observed to remain stable, and its dynamic behavior is well-damped, comparable to other established renewable energy systems. Generally, for both explored HRES systems  $t_{ct}$  is critical in determining the dynamic performance of the grid-tied HRES, particularly in terms of settling time for both frequency and voltage. The lack of a significant main effect for  $B$  on its own suggests that while  $B$  may contribute to the system's behavior, its

influence is more nuanced and likely context-dependent, interacting with control time to shape the overall response.

## **5.2. Recommendations**

Based on the findings of this research, several recommendations can be made to enhance the stability and performance of solar PV-wind grid-tie hybrid systems. These recommendations are aimed at system designers, engineers, and policymakers who are involved in the development and deployment of renewable energy technologies.

### **5.2.1. Optimization of System Design**

The design of a hybrid solar PV-wind system plays a crucial role in its stability. It is recommended that system designers optimize the configuration of the hybrid system by carefully balancing the contributions of solar PV and wind energy. This can be achieved through the use of advanced optimization algorithms that take into account factors such as local weather patterns, load profiles, and grid requirements. Additionally, the selection of high-quality power electronics, such as inverters and converters, is essential for ensuring that the system can operate reliably under varying conditions.

### **5.2.2. Implementation of Advanced Control Strategies**

To enhance both transient and steady-state stability, it is recommended to implement advanced control strategies that can dynamically adjust the operation of the hybrid system in response to changes in generation and load. These strategies may include adaptive control, model predictive control, and machine learning-based approaches that can predict and mitigate potential stability issues. Furthermore, the integration of

grid-supportive features, such as frequency regulation and voltage control, into the control system can help the hybrid system contribute to overall grid stability.

### **5.2.3. Integration of Energy Storage Systems**

The integration of energy storage systems, such as batteries or supercapacitors, is strongly recommended to improve the stability of hybrid solar PV-wind systems. Energy storage can provide several benefits, including the ability to smooth out fluctuations in power generation, enhance system inertia, and provide reserve power during disturbances. It is important to size and configure the energy storage system appropriately to match the specific needs of the hybrid system and the grid it is connected to.

### **5.2.4. Conducting Comprehensive Stability Assessments**

Before deploying hybrid solar PV-wind systems, it is recommended to conduct comprehensive stability assessments that include both transient and steady-state analyses. These assessments should consider a wide range of operating scenarios, including extreme weather conditions, grid faults, and varying load demands. By identifying potential stability issues early in the design process, system developers can implement appropriate mitigation measures and ensure the reliable operation of the hybrid system.

### **5.2.5. Collaboration with Grid Operators**

Given the importance of grid stability, it is recommended that hybrid system developers collaborate closely with grid operators to ensure that the integration of renewable energy does not compromise grid reliability. This collaboration may involve sharing data on system performance, coordinating the operation of the hybrid system with grid requirements, and participating in grid support services.

Additionally, it may be beneficial to explore the development of hybrid systems that are capable of operating in islanded mode, providing backup power to critical loads during grid outages.

### **5.2.6 Ongoing Monitoring and Maintenance**

To ensure the long-term stability and performance of hybrid solar PV-wind systems, it is recommended to establish ongoing monitoring and maintenance programs. These programs should include regular inspections of system components, performance evaluations, and the implementation of predictive maintenance techniques. By monitoring key parameters, such as voltage, frequency, and power quality, system operators can detect potential issues early and take corrective actions before they lead to instability.

### **5.2.7 Policy and Regulatory Support**

Finally, it is recommended that policymakers provide support for the development and deployment of hybrid solar PV-wind systems through favorable policies and regulations. This may include incentives for the integration of energy storage, funding for research and development in stability analysis, and the establishment of standards for the design and operation of hybrid systems. Additionally, policymakers should encourage the adoption of grid codes that facilitate the integration of renewable energy and promote grid stability.

## **5.3. Future Research Directions**

The findings of this research suggest several avenues for future research. One potential area of study is the development of more sophisticated models that can accurately capture the complex interactions between solar PV, wind energy, and the

grid. Additionally, further research is needed to explore the impact of emerging technologies, such as advanced power electronics and artificial intelligence, on the stability of hybrid systems. Finally, it would be valuable to conduct field trials and real-world demonstrations of hybrid solar PV-wind systems to validate the findings of this study and gain practical insights into their performance. Lastly, the transient and steady-state stability analysis of solar PV-wind grid-tie hybrid systems is a critical area of research that has significant implications for the future of renewable energy. By addressing the challenges of stability, this research contributes to the development of more reliable and resilient hybrid systems that can play a key role in the transition to a sustainable energy future.

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# APPENDIX

ETAP 1901.1 - (OLVT (DC Load Flow Analysis))

File Edit View Project Defaults RevControl Library Warehouse Rules Real-Time Datax Tools Window Help

Base OLVT OLVT Normal

ETAP (Default) 34.5 Phase Impedance Diagram dclF

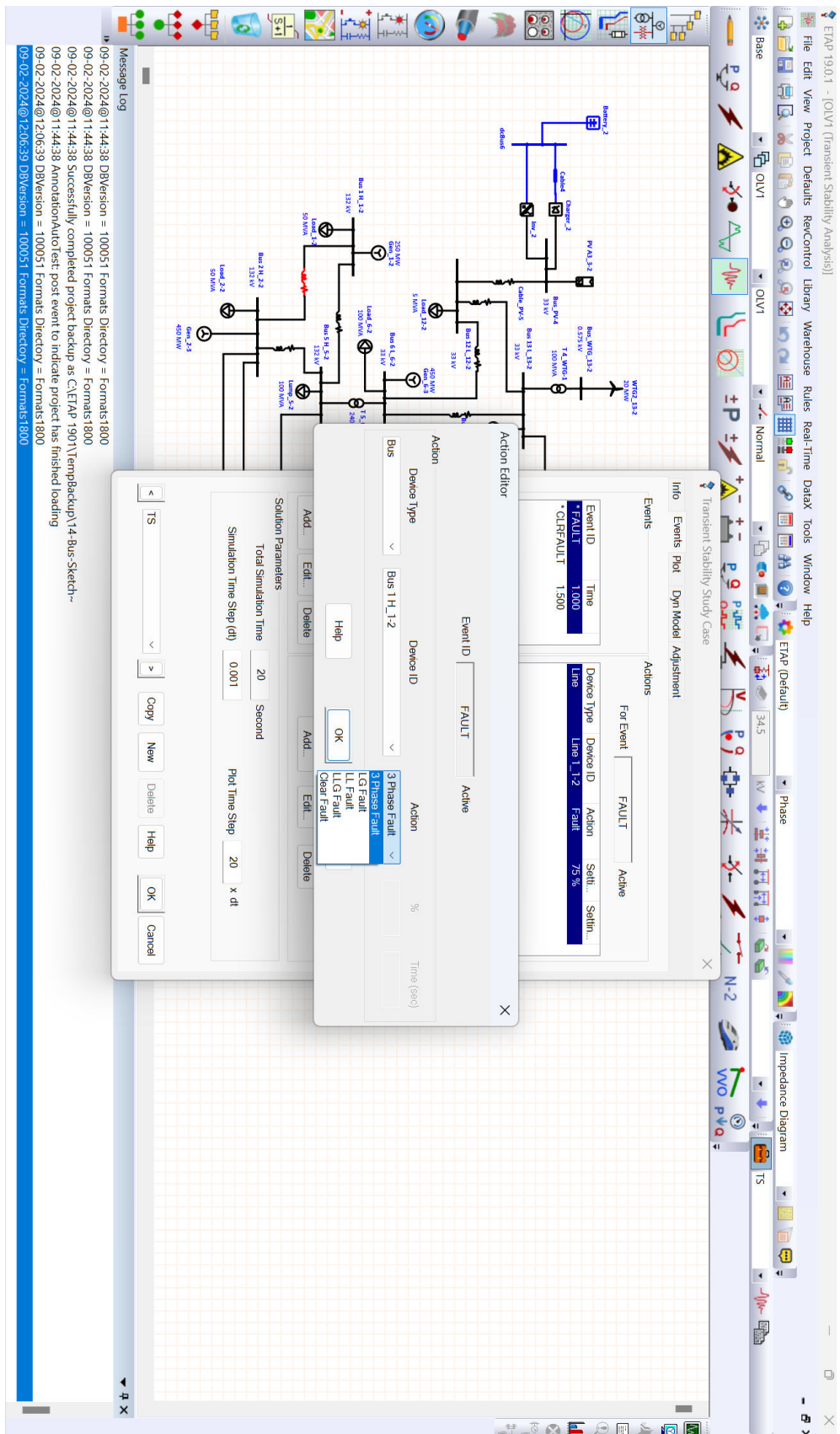
Message Log

- 09-02-2024@11:44:35 Loaded library C:\ETAP 1901\LIB\ETAPLib1901.lib Write Mode
- 09-02-2024@11:44:35 Opened C:\ETAP 1901\14-Bus-Sketch\14-Bus-Sketch.OTI cedse Project Editor
- 09-02-2024@11:44:38 DBVersion = 100051 Formats Directory = Formats\1800
- 09-02-2024@11:44:38 DBVersion = 100051 Formats Directory = Formats\1800
- 09-02-2024@11:44:38 Successfully completed project backup as C:\ETAP 1901\TempBackup\14-Bus-Sketch~
- 09-02-2024@11:44:39 Annotation\AutoTest post event to indicate project has finished loading

X:40204 Y: 8155 (Zoom Level: 22)

Base

ETAP interface



Fault initialization for Transient stability analysis

ETAP Plot Manager

FILE Home Export

Add Remove Vertical Horizontal Tabs Close Close Plot All

Layout Windows

Plot Explorer

Name	Created
TS.tsp	6/7/2024 3:37:15 PM
TS.tsp	6/7/2024 3:07:19 PM
TS.tsp	8/23/2024 2:17:10 PM

Device Type

Device Type	ID	kV
Syn Generator	Gen_8-2	11
Bus	Gen_6-3	33
Branch	Gen_1-2	132
Lumped Load	Gen_2-3	132
	Gen_3-2	132

Plot Type

Description	Checked
Power Angle (Relative)	<input type="checkbox"/>
Power Angle (Absolute)	<input checked="" type="checkbox"/>
Speed	<input checked="" type="checkbox"/>
MMW (Mechanical)	<input type="checkbox"/>
Mvar	<input type="checkbox"/>
Current	<input type="checkbox"/>
EFD	<input type="checkbox"/>
IFD	<input type="checkbox"/>
Machine 7	<input type="checkbox"/>

Combine Plot Plot

Power Angle (Absolute)

Speed

STUDY: Transient Stability

PLOTS: 2

POINTS: 2503

### ETAP Plot Manager Overview

