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Realized by
BAADJ Mounir / GHRIBI Atallah

Domain: Science and Technology
Field: Electrical Engineering
Option: Power Systems

THEME

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# Under Frequency Load Shedding in the Presence of Renewable Energy Sources

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Defense jury:

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# ملخص

طرح الاستخدام المتزايد لمصادر الطاقة المتجددة (RES) في أنظمة الطاقة تحديات جديدة للحفاظ على الاستقرار والتردد. مع زيادة الاعتماد على هذه المصادر المتقطعة للطاقة، تصبح موثوقية مصدر الطاقة أكثر أهمية من أي وقت مضى. فصل أحمال التردد المنخفض (UFLS)هو إجراء تحكم طارئ يستخدم لاستعادة توازن نظام الطاقة أثناء عدم التوازن. يعمل UFLS عن طريق التخلص من بعض الأحمال تلقائيًا عندما ينخفض تردد نظام الطاقة عن قيمة عتبة محددة مسبقًا. تبحث هذه الدراسة في أهمية UFLS في الحفاظ على مصدر طاقة موثوق ومدى فعاليته في منع التعتيم في نظام الطاقة، لا سيما في وجود لمصادر الطاقة المتجددة (RES).

لتقييم فعالية UFLS، استخدمنا برنامج ETAP وقمنا بمحاكاة سيناريوهين محددين في ثلاث حالات دراسية باستخدام نظام الاختبار "New England 39-bus". من خلال عمليات المحاكاة التي قمنا بها، استطعنا تقييم أداء UFLS في الأنظمة التقليدية وكذلك في الأنظمة التي تحتوي على مصادر الطاقة المتجددة .أظهرت نتائجنا أن UFLS هو إجراء فعال للتحكم في حالات الطوارئ يمكنه منع الظلام الدامس واستعادة استقرار التردد أثناء الاختلالات. علاوة على ذلك، قمنا بتحليل تأثير مصادر الطاقات المتجددة على UFLS وطورنا تصميمًا فعالًا لخطة UFLS يأخذ بعين الاعتبار مقدار الحمل في كل مرحلة ووقت استجابة مرحلة التردد. تعطي نتائج هذه الدراسة نظرة ثاقبة حول تأثير مصادر الطاقات المتجددة على استقرار نظام الطاقة وتوضح أهمية UFLS في الحفاظ على استقرار التردد.

**الكلمات المفتاحية:** فصل أحمال التردد المنخفض (UFLS)، استقرار التردد، مصادر الطاقة المتجددة (RES)، برنامج ETAP.

# Abstract

The increasing use of Renewable Energy Sources (RES) in power systems has posed new challenges to maintaining stability and frequency. As the reliance on these intermittent sources of energy increases, the reliability of the power supply becomes more critical than ever. Under Frequency Load Shedding (UFLS) is an emergency control action used to restore power system balance during an imbalance. UFLS works by shedding part of the load automatically when the power system frequency falls below a predetermined threshold value. This study investigates the importance of UFLS in maintaining a reliable power supply and its effectiveness in preventing power system blackouts, particularly in the presence of RES.

To evaluate the effectiveness of UFLS, we utilized the ETAP software and conducted simulations for two specific separation scenarios in three study cases using the "New England test system 39-noeud". Through our simulations, we assessed the performance of UFLS in traditional systems as well as in systems with the presence of RES. Our results showed that UFLS is an effective emergency control action that can prevent power system blackouts and restore frequency stability during imbalances. Furthermore, we analyzed the impact of RES on UFLS and developed an effective UFLS plan design that considers the amount of load in each stage and the response time of the frequency relay. These findings provide insights into the impact of RES on power system stability and demonstrate the importance of UFLS in maintaining frequency stability in power systems.

**Key words:** Under Frequency Load Shedding (UFLS), Frequency Stability, Renewable Energy Sources (RES), ETAP Software.

# *Résumé*

L'utilisation croissante des sources d'énergie renouvelable dans les systèmes électriques pose de nouveaux défis pour maintenir la stabilité et la fréquence. À mesure que la dépendance à ces sources d'énergie intermittentes augmente, la fiabilité de l'alimentation en énergie devient plus critique que jamais. Le délestage de charge en cas de sous-fréquence (UFLS) est une action de contrôle d'urgence utilisée pour rétablir l'équilibre du système électrique en cas de déséquilibre. L'UFLS consiste à déconnecter automatiquement une partie de la charge lorsque la fréquence du système électrique descend en dessous d'une valeur seuil prédéterminée. Cette étude examine l'importance de l'UFLS pour maintenir une alimentation en énergie fiable et son efficacité pour prévenir les pannes du système électrique, en particulier en présence de sources d'énergie renouvelable.

Pour évaluer l'efficacité de l'UFLS, nous avons utilisé le logiciel ETAP et mené des simulations pour deux scénarios de séparation spécifiques dans trois cas d'étude en utilisant le "New England test system 39-nœud". À travers nos simulations, nous avons évalué les performances de l'UFLS dans les systèmes traditionnels ainsi que dans les systèmes avec la présence de sources d'énergie renouvelable. Nos résultats ont montré que l'UFLS est une action de contrôle d'urgence efficace qui peut prévenir les pannes du système électrique et restaurer la stabilité de la fréquence lors des déséquilibres. De plus, nous avons analysé l'impact des sources d'énergie renouvelable sur l'UFLS et développé une conception efficace de plan d'UFLS qui tient compte de la quantité de charge à chaque étape et du temps de réponse du relais de fréquence. Ces résultats donnent un aperçu sur l'impact des sources d'énergie renouvelable sur la stabilité du système électrique et démontrent l'importance de l'UFLS pour maintenir la stabilité de la fréquence dans les systèmes électriques.

**Mots clés:** Délestage Sous-Fréquence (UFLS), Stabilité de Fréquence, Energies Renouvelables, Logiciel ETAP.

# *Dedication*

*We humbly dedicate this thesis to our beloved family, whose unwavering support and encouragement have been the bedrock of our academic journey. Your boundless love and unwavering belief in us have provided the strength and motivation to overcome challenges and pursue excellence.*

*We also extend our heartfelt dedication to our esteemed professor,* ***Prof. ARIF Salem****, whose exceptional guidance and expertise have profoundly shaped our understanding of the subject matter and nurtured our intellectual growth. Your unwavering dedication to education and unwavering commitment to our development have been invaluable blessings in our lives.*

*Furthermore, we dedicate this thesis to all those who ardently strive for a better and more sustainable future in the dynamic field of power systems. May the findings and insights presented within these pages ignite a spark of inspiration and propel further research endeavors in tackling the complex challenges of frequency stability.*

*To everyone who has been an integral part of this arduous journey, we extend our deepest gratitude for your unyielding presence, encouragement, and unwavering support. Your belief in us has been an enduring source of motivation, and we are forever grateful for your presence in our lives.*

*Mounir & Atallah*

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*In the name of Allah, the Most Gracious, the Most Merciful. We begin by expressing our heartfelt gratitude and acknowledging the blessings and guidance bestowed upon us throughout this journey by the Almighty. We are deeply grateful for His unwavering support and His grace that has enabled us to complete this thesis.*

*We would like to extend our sincere appreciation to our thesis supervisor,* ***Prof. ARIF Salem****. Your invaluable guidance, expertise, and continuous support have been instrumental in shaping our research and academic development. Your dedication to our success and commitment to nurturing our intellectual growth have been truly inspiring.*

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*We would like to extend our gratitude to our families and friends for their unwavering support, love, and encouragement throughout our academic journey. Your belief in our abilities and constant motivation have been a source of strength and inspiration.*

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*Mounir & Atallah*

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# *List of Abbreviations*

**UFLS -** Under Frequency Load Shedding

**RES -** Renewable Energy Sources

**ETAP -** Electrical Transient and Analysis Program

**AGC-** Automatic Generation Control

**PSS -** Power System Stabilizer

**DG -** Distributed Generation

**EMS -** Energy Management Systems

**ROCOF -** Rate Of Change Of Frequency

**SCADA -** Supervisory Control And Data Acquisition

**LFC -** Load Frequency Control

**PFR -** Primary Frequency Response

**SFR -** System Frequency Response

**HV -** High Voltage

**LV -** Low Voltage

**PV -** Photovoltaic

**WTG -** Wind Turbine Generator

**DLR** - Dynamic Load Restoration

**WSS -** Wide Area Stability System

**AUFLS -** Adaptive Under Frequency Load Shedding

**HVDC -** High Voltage Direct Current

**DFIG -** Doubly-Fed Induction Generator

**WAMPAC -** Wide Area Monitoring, Protection And Control

**WAMS -** Wide Area Monitoring Systems

# General Introduction

## Problem Statement

In today's world, electricity has become a basic necessity for people's daily lives, and industries rely heavily on it for their operations. With the growing global population, the demand for electricity is increasing rapidly, leading to the development of power systems with a significant capacity to produce and distribute electrical energy. However, ensuring the reliable and continuous supply of electrical power to consumers requires maintaining the stability and frequency of the power system. Power system stability refers to the ability of the system to maintain a balanced state despite changes in power demand or supply, while frequency stability refers to the ability of the power system to maintain a constant frequency, typically 50 or 60 Hz, which is necessary for the operation of electrical equipment.

The integration of Renewable Energy Sources (RES) into power systems has presented new challenges to maintaining power system stability and frequency stability. RES, such as wind and solar power, have been integrated into power systems to reduce greenhouse gas emissions and increase energy security. However, the variability and uncertainty associated with RES have made it challenging to maintain power system stability and frequency stability [1].

To overcome these challenges, new approaches to maintaining power system stability and frequency stability have been developed. Under Frequency Load Shedding (UFLS) is an emergency control action used to restore power system balance during an imbalance. UFLS is an essential tool in maintaining power system stability and frequency stability, as it prevents the risk of a complete blackout. UFLS works by shedding some load automatically when the power system frequency falls below a predetermined threshold value [1]. This restores the power balance, stabilizes the frequency, and ensures the continuous supply of electricity to consumers. This research thesis aims to investigate the role of UFLS in maintaining a reliable power supply and its effectiveness in preventing power system blackouts, particularly in the presence of RES.

## Objective Statement

The objective of this research thesis is to:

1. Investigate the importance of Under Frequency Load Shedding (UFLS) for power system stability and frequency stability.
2. Develop effective UFLS plans for power systems using ETAP software to simulate UFLS scenarios and analyze their impact on power system stability and frequency stability.

3. Explore the role of UFLS in emergency control plans and its effectiveness in preventing power system blackout.
4. Investigate the challenges of implementing UFLS in power systems with Renewable Energy Sources (RES).
5. Propose solution to overcome the challenges of implementing UFLS in power systems with RES.

## Thesis Outline

To achieve the objectives outlined above, the present thesis is outlined in three chapters as follows:

**Chapter I:** provides a solid foundation for understanding power system stability and frequency stability. It offers a comprehensive introduction to the different types of power system stability and frequency stability, including rotor angle stability, voltage stability, and frequency stability. The chapter also highlights the importance of frequency control, which is crucial in maintaining a stable frequency within a narrow range under normal and abnormal operating conditions. Additionally, it provides an overview of power system developments with renewable energy sources, which have become increasingly important in today's world.

**Chapter II:** explores Under Frequency Load Shedding (UFLS), an emergency control action used to maintain power system stability and frequency stability. The chapter discusses important parameters for UFLS, offers a general overview of UFLS, and examines the impact of distributed generation and new technologies on UFLS.

**Chapter III:** in this chapter, the ETAP software is introduced, and its ability to simulate UFLS scenarios is demonstrated. The simulations results of various scenarios are analyzed to evaluate the effectiveness of UFLS in maintaining power system stability and frequency stability. The chapter provides a detailed analysis of the simulation results and their implications for UFLS implementation in power systems.

Finally, this work concludes with a comprehensive conclusion that summarizes the key findings of the study and offers valuable recommendations for future research in the field of under frequency load shedding and power system stability.

# Chapter I

## *Power System Stability*

## I.1 Chapter Introduction

Power system stability can be defined as the ability of an electric power system, under a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, while ensuring that most system variables remain bounded, and the entire system remains intact. In other words, the system should remain stable throughout the disturbance, and any instability that occurs in one part of the system should not propagate to the rest of the system.

As the operating conditions of a power system are constantly changing, its stability depends on the type of disturbance and the operating state prior to the disturbance. Disturbances can be small or large, and their impact on the power system depends on the system's design and modelling. It is not practical to design a power system that is resistant to any type of disturbance, so the focus should be on ensuring that the system remains stable in the case of the most severe credible contingency [1].

A power system's response to a disturbance can vary depending on the type of disturbance and the individual characteristics of the system. For example, changes in frequency or voltage can cause changes to the system, affecting prime mover governors and other protection devices. It is essential to ensure that these devices respond correctly to the relevant disturbance to prevent the tripping of parts of the power system, which could cause system instability [2].

If a fault occurs in a complex power system, it may be necessary to split it into two or more "islands" to preserve as much generation and load as possible while keeping the rest of the system stable until the fault has been cleared. Once the fault has been cleared, the islands can reconnect to the rest of the system.

## I.2 Types of Power System Stability

Power system instability can arise from various causes, including the magnitude of the disturbance, the physical characteristics of the devices involved, and the time frame in which the system stability must be evaluated. Based on these key factors, power system stability can be classified into the following categories [2]:

- Rotor Angle Stability,
- Voltage Stability,
- Frequency Stability.

### I.2.1 Rotor Angle Stability

Rotor Angle Stability is a critical aspect of power system stability that ensures the synchronous machines within an interconnected power system remain in synchronism after a disturbance. Maintaining balance between the electromagnetic and mechanical torque of each synchronous machine is crucial for the system to remain intact [2, 3].

In a stable power system, the input mechanical torque of each generator equals the output electromagnetic torque, and their speeds remain constant. However, if the rotors of some generators accelerate or decelerate, it can cause one generator to run faster than others, leading to a difference in angular stability. This creates a power angle relationship between the generators, resulting in the slower generator transferring part of its load to the faster generator to reduce the speed difference and trigger rotor angle separation [2].

The stability of the power system relies on two key components: the synchronizing torque component, which is in phase with the rotor angle deviation, and the damping torque component, which is in phase with the speed deviation. If the restoring torques resulting from these components are sufficient, the system remains stable. Otherwise, rotor angle instability can occur [2, 3].

### I.2.2 Voltage Stability

Voltage stability is a critical aspect of power system stability that ensures the maintenance of steady voltages at all buses after a disturbance . In other words, the power system must maintain an equilibrium state between load supply and demand, even in the face of contingencies. When a disturbance occurs, voltages at the buses may rise or fall, leading to the loss of load in some areas, tripping of transmission lines, and other issues.

Voltage instability can cause voltages at the buses to drop progressively. If two machines operate in an unstable condition after losing synchronization between them, protective elements attempt to separate these machines to keep these areas isolated until the contingency has been cleared. However, if separation is not possible, large voltage oscillations between low and high points can occur. If the voltage drops to a very low value, the power system is likely to experience voltage collapse, which could result in a blackout [2].

Voltage stability depends on the balance between load and demand in the power system. If one part of the system is heavily loaded, it can lead to the tripping of transmission lines and cause voltage to drop. Power system regulating mechanisms will attempt to restore power to meet the load demand at normal voltage, but this can also result in additional stress and overload to the power system, leading to voltage instability.

There are two types of voltage stability: large-disturbance voltage stability and small-disturbance voltage stability [2]. Large-disturbance voltage stability refers to the ability of the system to maintain steady voltages after a severe perturbation, such as the loss of a generator or system faults. To determine large-disturbance system stability, the nonlinear response of the power system over a period of time must be examined to capture the performance and interactions of devices such as motors. Small-disturbance voltage stability, on the other hand, refers to the ability of the power system to maintain steady voltages during small disturbances, such as incremental changes in system load. Determining how the system voltage responds to small disturbances requires consideration of the load characteristics and different controls at the given instant of time [2].

### I.2.3 Frequency Stability

Frequency stability refers to the capability of a power system to maintain a stable and consistent frequency following a disturbance that has caused an imbalance between generation and load. To achieve this, each generator is equipped with a governor that facilitates primary frequency control, ensuring that the frequency remains close to its nominal value. Additionally, central control centers play a vital role by providing supplementary control measures through generation allocation. In the short term, frequency instability can arise if there is insufficient under frequency load shedding, which leads to a gradual decline in frequency and potentially results in a blackout. On the other hand, long-term frequency instability may occur due to decay in frequency caused by prime-mover governing systems associated with steam turbine overspeed controls.

It is crucial to maintain proper frequency stability in power systems to prevent detrimental consequences and ensure the reliable operation of the grid. By implementing effective control mechanisms, such as governor systems and load shedding strategies, power system operators can effectively address frequency deviations and maintain a stable frequency profile throughout various disturbances.

Figure I.1 illustrates the classification of power system stability based on the physical nature of the instability mode, disturbance sizes, processes involved, and time frames [3]. This classification provides a comprehensive framework for understanding and categorizing different stability phenomena that can occur in power systems.

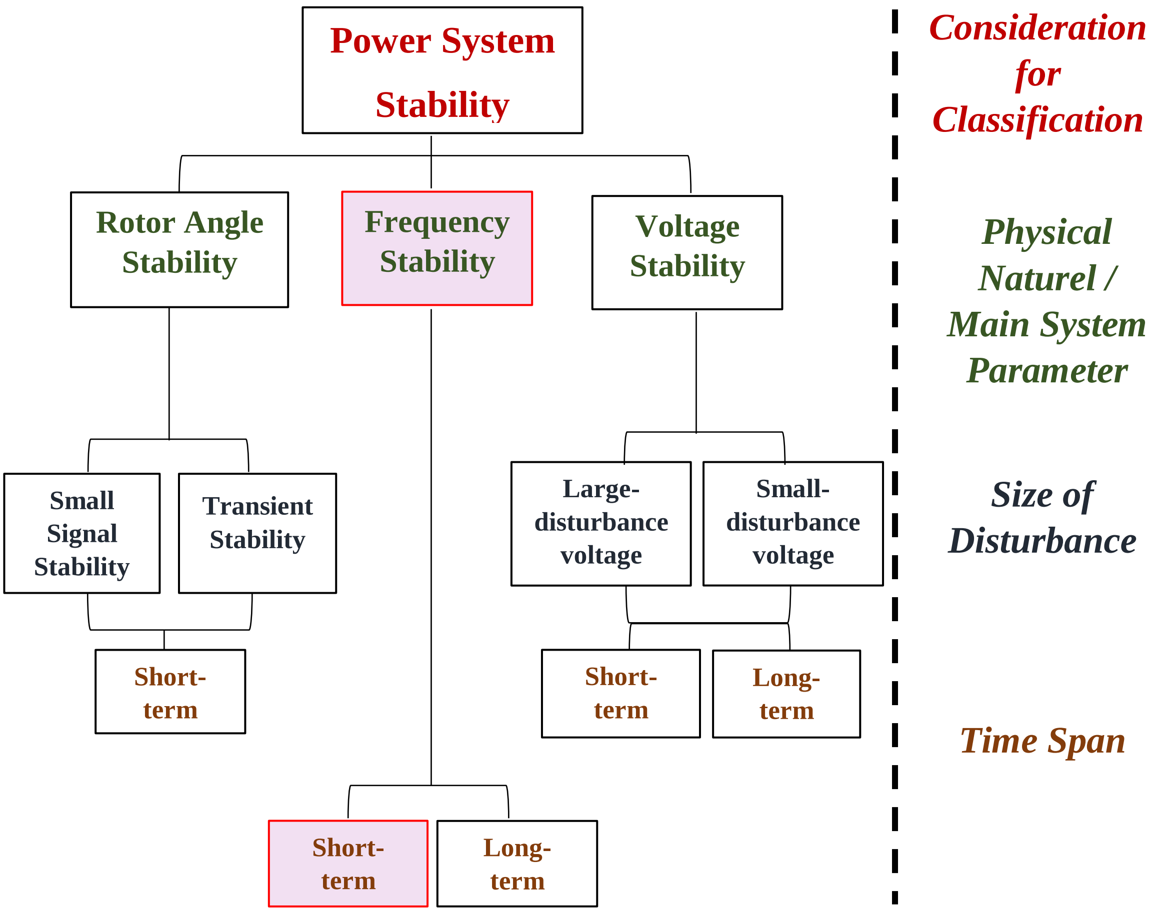


Figure I.1. Classification of power system stability [2]

## I.3 Types of Frequency Control

The control of frequency in power systems involves distinct phases that depend on the response of generators to disturbances. The first phase, known as inertial response, occurs when the frequency controllers of power plants remain inactive, and generators release or absorb their kinetic energy to counterbalance frequency changes. This phase aims to mitigate significant frequency deviations. The subsequent phases, primary and secondary control, involve the activation of controllers to restore and stabilize the frequency towards its nominal value. If the frequency deviation persists, the tertiary frequency control comes into play, providing additional adjustments to the power system. In cases of substantial frequency deviations, under frequency load shedding is triggered to prevent a blackout [2].

### I.3.1 Inertial Response

The frequency deviation, which is a result of an imbalance between generation and load, can be expressed by this equation [5]:

$$P_m - P_e = \frac{d\left(\frac{1}{2}J_{\text{system}} \cdot \omega_{el}^2\right)}{dt} \tag{1}$$

Where $P_m$ is generated power, $P_e$ is electrical power, $J_{\text{system}}$ is the inertia of the system and $\omega_{el}$ is electrical angular frequency. The derivative side of the Eq. (1) is derivative of kinetic energy stored in all generators of the power system. The kinetic energy stored in the shaft of the single generator can be expressed as a proportion to its power and is called inertia constant $H$ [5]:

$$H = \frac{\frac{J_{gen}}{p^2} \cdot {\omega_{el,0}}^2}{2 \cdot S_{gen}} \tag{2}$$

Where $p$ is the number of the pole pairs, $S_{gen}$ is a nominated apparent power, $\omega_{el,0}$ is the nominal system frequency. By putting Eq. (1) and Eq. (2) together and assuming that there is a whole power system then we get this expression in per unit [5]:

$$P_m - P_e = 2 \cdot \sum_{i}^{n} \frac{H_{igen} S_{igen}}{S_{\text{base}}} \cdot \bar{\omega}_{el} \cdot \frac{d\bar{\omega}_{el}}{dt} \tag{3}$$

$$= 2 \cdot H_{system} \cdot \bar{\omega}_{el} \cdot \frac{d\bar{\omega}_{el}}{dt} \tag{4}$$

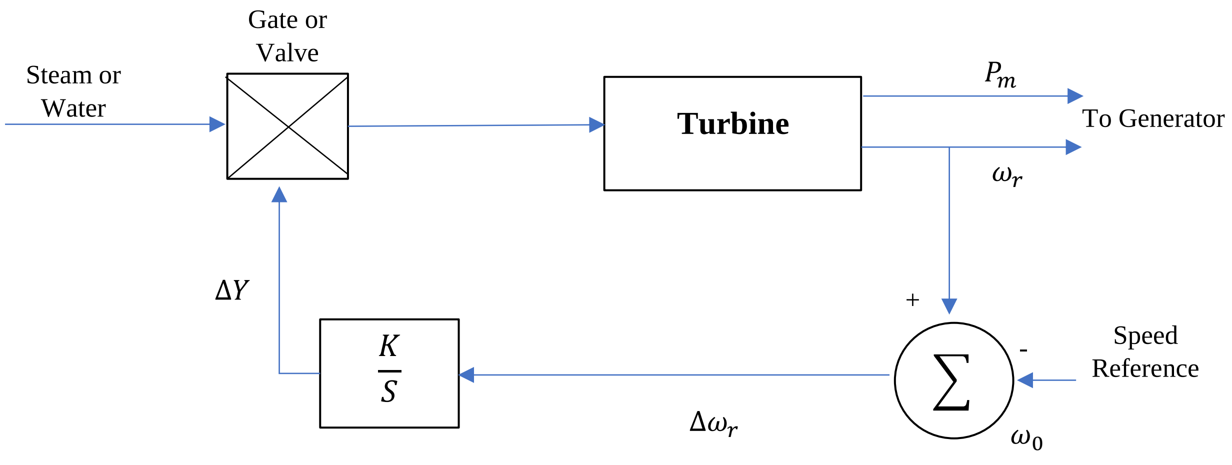
Assuming that $\bar{\omega}_{el}$ is approximately one, then the Rate Of Change Of Frequency (ROCOF) can be determined by using this equation:

$$\frac{d\bar{\omega}_{el}}{dt} = \frac{\bar{P}_m - \bar{P}_e}{2 \cdot H_{\text{system}}} \tag{5}$$

According to the Eq. (5), ROCOF depends on system inertia and magnitude of the power imbalance of the system [5]. There are two main factors, which affect the system inertia and they are the number of the generators in the system and the inertia of each generator. The traditional power plants consist of synchronous generators and they have very strong coupling between their rotational speed and the electrical frequency. Hence, their inertia contributes to the inertia of the whole system. In the era of renewables, there is no coupling between the wind turbines and photovoltaic units and the actual generators in the grid, therefore the system inertia will be very low. Low system inertia in the case of frequency deviation will lead to a high ROCOF. High ROCOF can lead to a cascade disconnection of some renewables generation [5].

### I.3.2 Primary Frequency Control

Primary frequency control should be available within a few seconds after disturbance has occurred. The governor of the generator provides primary frequency control. On the basis of the frequency deviation, by comparing measured rotor speed of generator and reference speed, governor decides if turbine's gate needs to open or close in order to increase or to decrease steam flow. By decreasing or increasing the steam flow, mechanical power output of the generator changes and in turn it reduces frequency deviation [2]. Figure I.2 illustrates block diagram of a simple governor controller which provides primary frequency control.



$P_m$ - mechanical power $\omega_r$ - rotor speed
$\omega_0$ - speed reference $\Delta Y$ - valve position

Figure I.2. Block diagram of simple governor controller implementing primary frequency control [5]

As it can be seen in Figure I.2, the measured rotor speed $\omega_r$ is compared with the reference speed $\omega_0$ and as a result of this comparison we get the speed deviation $\Delta\omega_r$.This signal is amplified ($K$) and integrated ($1/S$) to produce a control signal $\Delta Y$ which dictates the valve position. In the case of a load increase the frequency initially drops at a rate determined by the inertia. As the speed drops, $P_m$ starts to increase. This causes a reduction in the rate of the decrease of the speed and then an increase in speed when turbine power is in an excess of the load power.

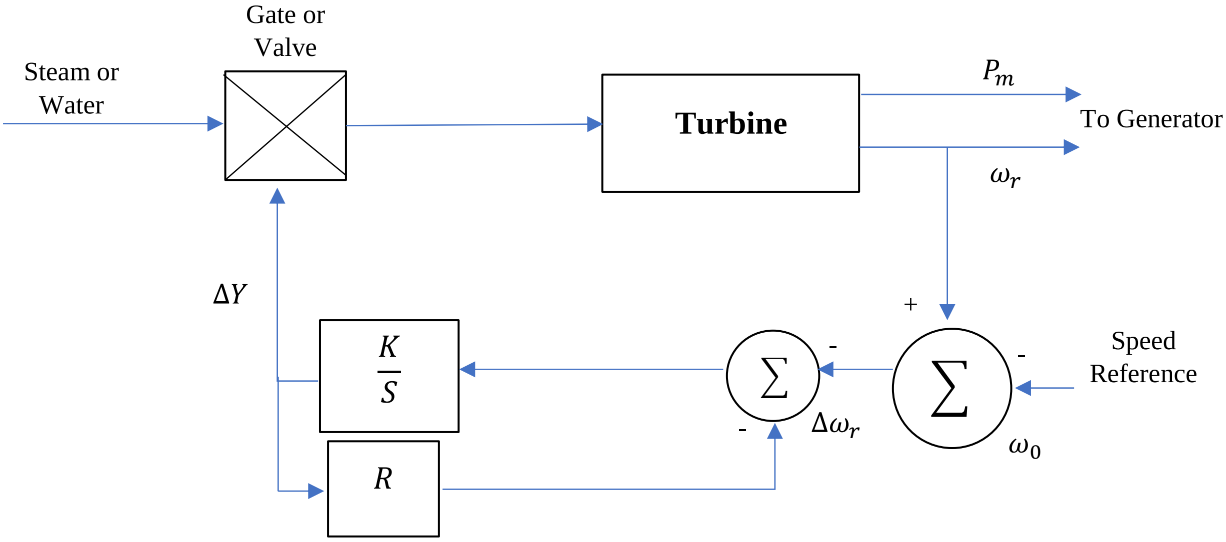
The governor uses its speed-droop characteristics to close or to open the valve which then reflects in a change of the turbine mechanical power. Speed regulation or droop $\rho$ equals to the change in frequency $\Delta f$, normalized to the nominal frequency, $f_n$, divided by the change in the electrical power output, $\Delta P$, normalized to a given power base, $P_n$. It can be represented by Eq. (6) [2]:

$$\rho = \frac{\frac{\Delta f}{\Delta f_n}}{\frac{\Delta P}{\Delta P_n}} \text{ [per unit]} \tag{6}$$

The inverse of the speed droop is $R$ and it is defining the stiffness of the generator. Speed droop is represented as a negative feedback control loop in the generator system which is added to the load reference set point to determine the position of the turbine gate.

The change in the relationship between speed and the gate position can be determined on the basis of the load reference set point.

The block diagram of the process can be seen in the Figure I.3.

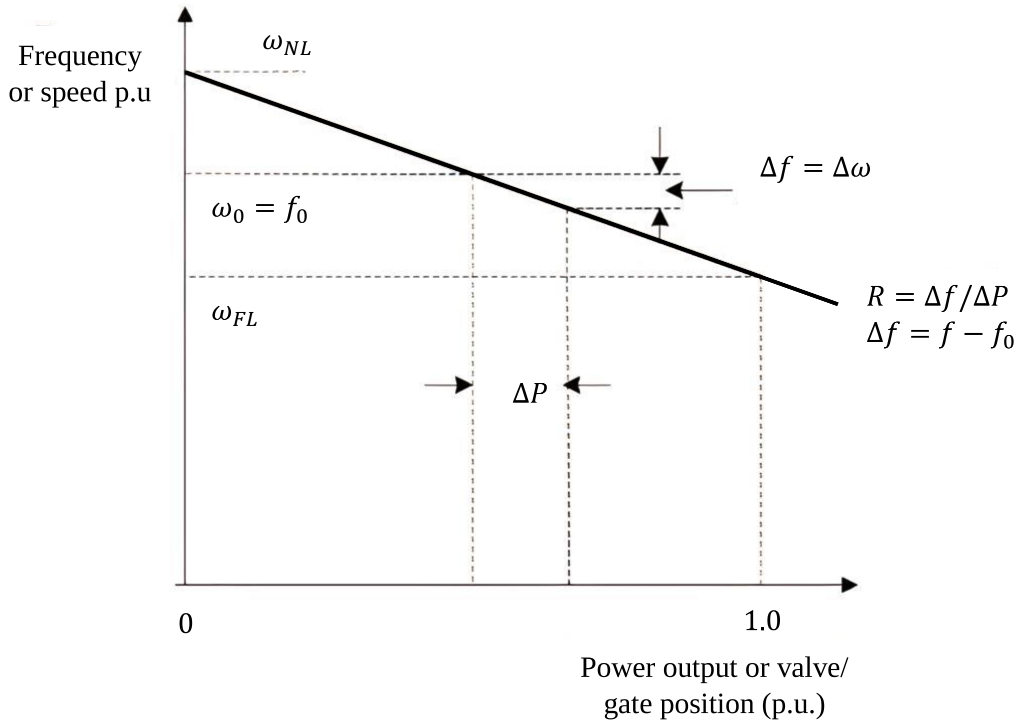


$P_m$ - mechanical power $\omega_r$ - rotor speed
$\omega_0$ - speed reference $\Delta Y$ - valve position

Figure I.3. Block diagram of the governor controller with the addition of speed-droop feedback implementing primary frequency control [5]

The relationship between speed of generator and position of the valve could be seen in the Figure I.4. This relationship shows ideal characteristics of a governor and speed droop. In the reality, governor characteristics of the steam turbine and hydraulic turbine are not ideal.

It implicates that frequency deviation may not be in linear relationship with the disturbance or the change in the load.



$\omega_{NL}$-steady-state speed at no load $\omega_{FL}$-steady-state speed at full load

$\omega_0$ - nominal speed

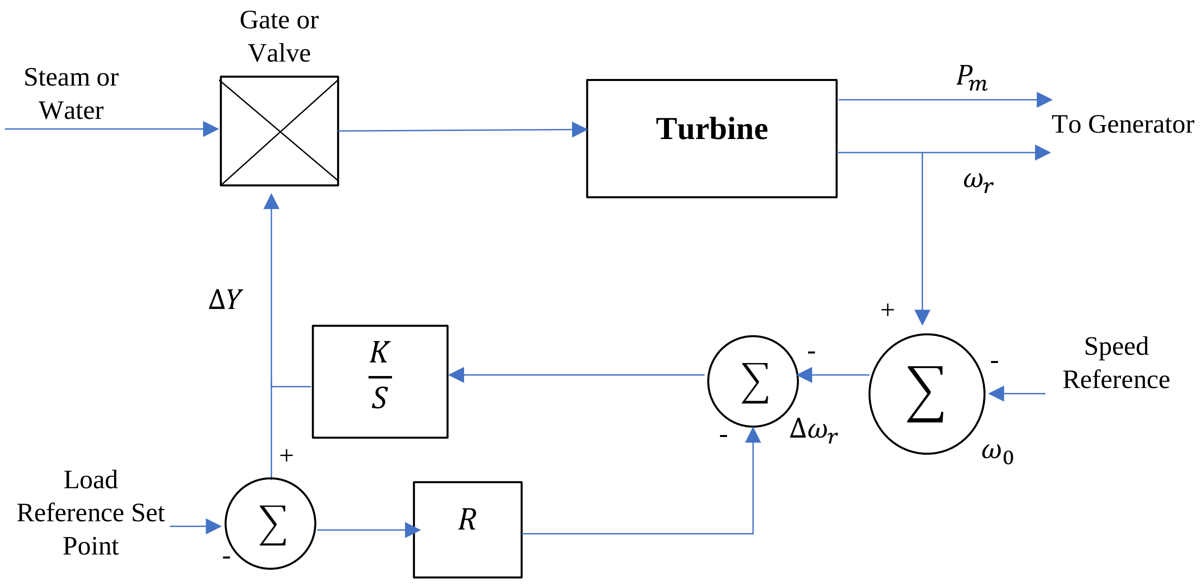
Figure I.4. Ideal steady state characteristics of a governor with speed droop

Most of the primary control units have dead bands around their nominal system frequency which protects the rest of the system from reacting to the any small frequency deviations which is not going to cause any interruptions in the system. If the machine would have responded to each of these small changes it could lead to the machines control systems prematurely ageing and it would increase cost of primary control without any benefits [6]. The size of the dead band on the speed governor decides when the primary control mechanisms are going to start acting. If frequency deviation is small, it remains within the dead band, there would be no response from the governor. If the frequency deviation is large and it exceeds the size of the dead band, then primary control mechanisms will become active [7].

Primary frequency control is classified as a fast acting of frequency control and it has been measured in MW per seconds. This means that primary frequency control is an essential part of the system’s ability to keep frequency close to the nominal and it minimises the initial frequency deviation after occurrence of disturbance [7].

### I.3.3 Secondary Frequency Control

Primary control prevents frequency from dropping below certain value, but it does not restore frequency to its nominal value. By using speed droop on its own, primary control would never been able to restore frequency to its nominal value. The secondary frequency control adjusts load reference set point on some or all generators. Adjustment of load reference set point of the generators will allow generated power to increase or decrease and this is going to restore frequency to its nominal value. This has been accomplished through speed-changer motor. Figure I.5 shows block diagram of the secondary frequency control [4].



$P_m$ - mechanical power $\omega_r$ - rotor speed
$\omega_0$ - speed reference $\Delta Y$ - valve position

Figure I.5. Block diagram of the governor controller with the addition of a feedback loop that allows the load reference set point to be changed [5]

In the isolated power systems, individual generators decide whether to adjust its load reference set point. In the interconnected power systems, the main aim of secondary frequency control is to restore balance between load and generation in each area. This means that frequency in all areas has to return to the nominal and that interchange power with the neighbouring areas should return to the certain value [2]. Secondary control should actually be active only in the area where there is a power imbalance. If there are two interconnected areas and if there is a power imbalance in the area 1, then secondary control should only activate in the area 1 and not in the area 2. In an interconnected system, where power imbalance cannot be corrected within the affected area due to the less than necessary generation reserve, other areas will transfer the power to the area which needs it through the tie lines between the areas [2]. Transfer power between the areas will result in changes in the generated power of these areas.

Therefore, each area will have to allow their tie-line flow limits. This type of the control is known as Automatic Generation Control (AGC).

Secondary frequency control is slower than primary frequency control and it should be available from 10 seconds up to 15 minutes after the occurrence of the disturbance [6].

### I.3.4 Tertiary Frequency Control

Tertiary frequency control is the slowest of the three frequency control actions, following primary and secondary control. It is activated if the frequency deviation lasts longer than 15 minutes and is measured in MW/min. When primary and secondary controls are insufficient to restore the frequency to the nominal value within a certain time frame, tertiary frequency control takes centralized actions to balance power [2].

Coordinated actions that tertiary control takes include changes in dispatch to follow the load and changes in generating units to redistribute reserves. This can involve increasing generation to replace generation losses and replacing generating units that have been exhausted from helping restore the frequency to the nominal value. The location of the reserve is more important than the quantity of the reserve, as it must be located in the appropriate area of the power system to be utilized quickly for balancing power.

Tertiary frequency control can be operated either automatically or manually, depending on the operator's preferences [6].

### I.3.5 Emergency Frequency Control

Under Frequency Load Shedding (UFLS) is an emergency frequency control action which activates when frequency drops below the critical value. UFLS does not activate for small fluctuations in load. It is only responsible for keeping frequency stable after disturbance has occurred. If the disturbance occurs and the frequency starts dropping towards certain threshold, UFLS activates. There are different triggers that activate the scheme. Some of them are the absolute value of the frequency, Rate Of Change Of Frequency (ROCOF), the time spent below certain frequency value and many more. UFLS operates through relays, which control the circuit breakers. Circuit breakers open or close depending on the type of disturbance. This is an automatic operation which is usually executed in stages. In each stage relevant amount of load is shed. If too big amount of load is shed all at once, frequency will rise above its nominal value and this will lead to the possible over shedding of the load. Load shedding is usually done by disconnecting the part of the load and it is an automatic operation whereby connecting the load to the power system again is a manual process which requires some additional time [15].

## I.4 Power System Developments with Renewable Energy Sources

Renewable energy refers to energy sources that are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat [8]. These energy sources can be utilized through renewable energy systems (RES) that can be installed at the transmission level with large capacities or at the distribution level on a smaller scale. Distributed Generation (DG) connected to the distribution network is known as Distributed Energy Resources (DER). Common RES technologies include hydro, biomass, biogas, solar power, wind power, and geothermal power. Additionally, grid-connected electricity storage can be classified as a type of renewable energy system.

### I.4.1 Wind Power

Wind power is a renewable energy source that harnesses the kinetic energy of moving air to generate electricity. Wind turbines play a crucial role in converting the wind's rotational energy into electrical energy through the use of an electrical generator. The location of a wind turbine greatly influences its annual energy production. However, wind and solar power are characterized by intermittent generation, which refers to the unpredictable variations in their output over time.

There are two main types of wind turbines: fixed-speed and variable-speed. Fixed-speed turbines utilize squirrel cage induction generators (SCIGs) and control the generated power through active or passive stalling or by adjusting the blade angle. These fixed-speed wind turbines are coupled by inertia, which allows them to contribute to frequency control. Capacitors are used to compensate for reactive power in fixed-speed turbines.On the other hand, variable-speed turbines adjust their rotational speed to maximize aerodynamic efficiency across a wide range of wind speeds. These variable-speed wind turbines, being not coupled by inertia, do not contribute to frequency control. However, they control reactive power to maintain a power factor close to unity. Variable-speed wind turbine generator systems can employ Double-Fed Induction Generators (DFIGs) or Generators with Front-End Converters (GFECs) [10].

The global installed capacity of wind power has experienced significant growth in recent years, with an astonishing increase of over 1000% between 2004 (47 GW) and 2018 (539 GW) [9]. Offshore wind energy sources are currently more costly compared to onshore wind due to technical challenges associated with offshore turbine construction and grid connection. However, onshore wind energy remains the most cost-effective renewable energy option. The development of wind power and the advancements in power electronics converters have played a significant role in the growth and efficiency of wind energy generation worldwide [11].

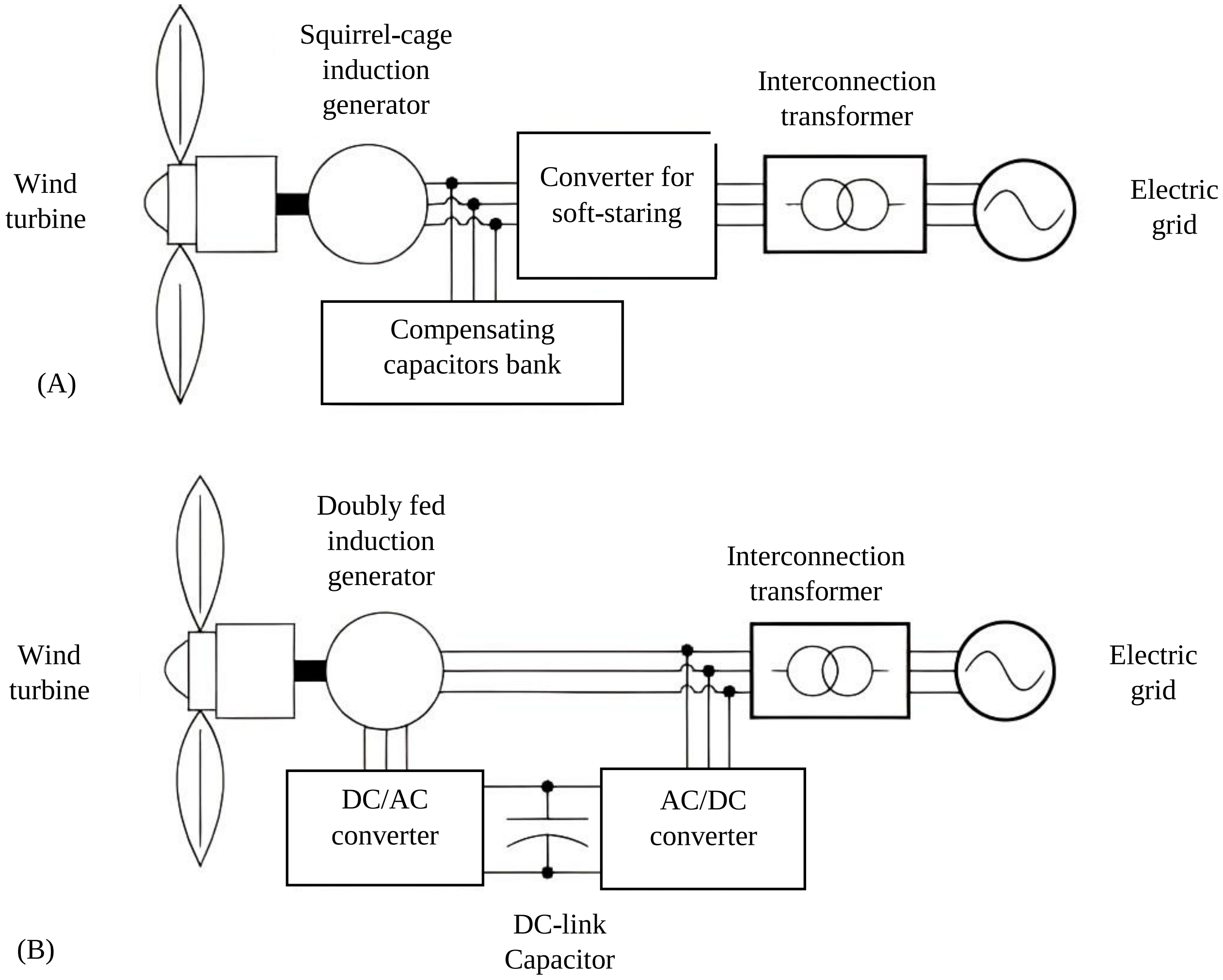


Figure I.6. The two main types of wind turbines: (A) Fixed speed and (B) Variable speed [10]

### I.4.2 Solar Power and Energy Storage

Solar power, while a rapidly growing renewable energy source, has the inherent limitation of intermittency, with energy production fluctuating throughout the day and being unavailable at night. This presents a challenge in maintaining a stable power supply since energy must be consumed in real-time and cannot be easily stored. To address this challenge and ensure a continuous power supply, the integration of energy storage with solar power systems proves to be a promising solution [13].

By incorporating energy storage systems, excess solar energy generated during the day can be efficiently absorbed and stored for later use. These stored reserves are then deployed during nighttime hours, enhancing the overall stability and reliability of the power system. Moreover, the combination of solar power and energy storage offers additional benefits to the grid. For instance, during periods of high demand or when solar power production is low, the energy storage system can provide backup power, contributing to grid resilience [12].

To optimize the integration of solar power and energy storage, a Power Electronics (PE) interface plays a vital role. This interface enables better control and management of the energy flow between the solar panels, energy storage, and the grid. By leveraging power electronics technologies, the system can efficiently regulate the transfer of energy, ensuring optimal utilization and maximizing overall system efficiency. Therefore, the combination of solar power and energy storage, facilitated by a Power Electronics interface, not only mitigates the intermittent nature of solar energy but also provides valuable services to the power system, such as backup power during high-demand periods. This integrated approach contributes to a more reliable, stable, and efficient power supply [12, 13].

### I.4.3 Distributed Generation

Distributed generation refers to the installation of power generation units at or near the point of energy consumption, typically within distribution networks. This approach offers numerous benefits, including reduced transmission losses, increased grid resilience, and improved efficiency. By generating electricity closer to where it is needed, the need for extensive transmission infrastructure can be minimized, resulting in cost savings and improved overall system performance. The integration of generation resources with distribution networks has witnessed remarkable growth in recent years, driven by government support for low-carbon technologies. The future outlook for distributed generation is promising, with substantial capacity expected to be installed globally. By 2035, distributed wind turbines are projected to reach a capacity of 8 GW, while solar power is anticipated to reach 10 GW. Overall, the capacity of all distributed generation sources is expected to reach 27.5 GW by 2035 [13].

## I.5 The Impact of Integrating (RES) Into the Power System

The integration of renewable energy sources (RES) into the power system has a range of impacts, both positive and negative.

Benefits of Integrating RES [19]:

- Increased Renewable Generation Capacity: Integrating RES leads to a significant increase in renewable generation capacity. Solar, wind, and other renewable sources can generate electricity on a large scale, reducing reliance on fossil fuel-based power plants. This shift towards cleaner energy sources contributes to carbon emissions reduction and helps combat climate change.

- Reduced Environmental Impact: One of the key benefits of integrating RES is the reduced environmental impact compared to traditional power generation methods . RES produce minimal or no greenhouse gas emissions during operation, resulting in cleaner air and reduced pollution levels. This positive environmental impact contributes to the overall sustainability of the power system.
- Market and Policy Frameworks: The integration of RES often requires adjustments in market and policy frameworks to support their penetration and incentivize investment. Market structures and pricing mechanisms may need to adapt to accommodate the variable nature of renewable generation and incentivize flexibility services. Additionally, supportive policies, such as renewable energy targets, feed-in tariffs, and tax incentives, are crucial to drive investments in RES integration and remove barriers to their deployment.

However, the integration of RES also presents several challenges that need to be addressed for a successful transition. These challenges include the following [19]:

- Variable and Intermittent Generation: The variability and intermittency of RES generation pose challenges for grid operators in maintaining a stable and reliable power system [13]. Solar and wind power generation are dependent on weather conditions, resulting in fluctuations in power output. This unpredictability requires careful forecasting, grid management, and coordination to ensure supply meets demand and maintain grid stability.
- Grid Balancing and Stability: The integration of RES adds complexity to grid balancing and stability. As RES generation is contingent on weather patterns, sudden changes in generation levels can impact the balance between electricity supply and demand, leading to frequency deviations and potential instability in the power system. The inherent characteristics of RES, such as their variable and intermittent nature, can result in challenges related to frequency stability and low inertia [2, 19].
- Grid Infrastructure Upgrades: Integrating a higher share of RES may necessitate upgrades to the existing grid infrastructure. Transmission lines, substations, and control systems may require enhancements to handle increased renewable generation capacity. The integration of RES often occurs in remote or distant areas, requiring transmission

infrastructure expansion to transport the generated energy to load centers. These upgrades are essential to ensure efficient and reliable transmission of renewable energy across the power system.

- Energy Storage and Flexibility: The intermittent nature of RES generation highlights the need for effective energy storage solutions and system flexibility. Energy storage technologies, such as batteries, pumped hydro storage, and emerging solutions like hydrogen storage, play a crucial role in balancing supply and demand mismatches caused by variable RES generation. These technologies store excess renewable energy during periods of high generation and release it when generation is low, ensuring a stable power supply.
- Grid Integration and Interconnection: The integration of RES requires careful planning and coordination across multiple power systems and geographical regions [2]. This involves establishing robust interconnections and coordination mechanisms to facilitate the smooth flow of renewable energy across the grid. Integration challenges can arise due to differences in grid codes, regulatory frameworks, and market designs, necessitating harmonization efforts to enable seamless RES integration.

## I.6 Chapter Conclusion

In this chapter, we have discussed the different types of power system stability and their importance in maintaining a secure and reliable power system. We have defined the concept of frequency stability and its control mechanisms, including primary, secondary, and tertiary frequency control, as well as emergency frequency control. It is essential to maintain frequency stability, as any imbalance between generation and load can cause severe disturbances in the power system, leading to blackouts and other undesirable consequences.

Furthermore, the chapter addressed the growing significance of renewable energy sources in power system developments. Renewable energy sources such as wind and solar are becoming more prevalent, and their integration into power systems poses new challenges for frequency control and stability. Power system stability is a critical aspect of power system operation, and frequency stability is an essential component of this stability and with the increasing use of renewable energy sources, the power system's stability becomes more complex.

# *Chapter II*

## ***Under Frequency Load Shedding***

## II.1 Chapter Introduction

The stability of the power system depends on various factors, including frequency. When the frequency drops below the nominal value and the turbine operates in a low-frequency condition, it can cause damage to the steam turbine [15]. To prevent such situations, control and protection measures must be taken.

Under Frequency Load Shedding (UFLS) is the most suitable frequency control mechanism as it sheds the load according to the mismatch between generated and electrical power [15, 16].

Each power system has its own UFLS scheme designed to activate whenever there is an indication that the system is in possible danger. The most effective way of achieving this is by monitoring and measuring the system frequency of the grid. Once the frequency falls close to the pre-defined threshold, appropriate actions must be taken to prevent a further drop in frequency and avoid a system collapse [17].

## II.2 Power System Blackouts

Over the past few decades, electric power systems around the globe have undergone massive changes, including the rapid growth of installed capacities, restructuring and deregulation of the electrical industry, and extensive integration of renewable energy sources. However, these changes have also led to more frequent and severe occurrences of cascading failures and blackouts. While the exact mechanics of power system blackouts are complex and vary dramatically in different situations, many blackouts have followed a common pattern, as shown in Figure II.1.

The causes of power system blackouts can include dynamic or static stability loss, voltage collapse, voltage instability in transmission networks, inappropriate load shedding, and multiple tripping of overloaded lines, among others. Potential improvement schemes would include grid reinforcement, increasing tie-line capacity, re-designing load shedding strategies, planning suitable locations for new generators, installing more measurement and control systems, optimizing reactive power and voltage controls, installing advanced protection relays, and implementing automatic operations and alarms during severe incidents. Modern power systems should be capable of self-healing and preventing blackouts, including automatic re-closing of transmission lines and component reintegration. After a power system blackout, the system should also be restored automatically and quickly [16].

In addition, modern power systems can increase their stability and avoid blackouts using state-of-the-art controllers, sensors, and products such as (HVDC) elements or novel special protection schemes.

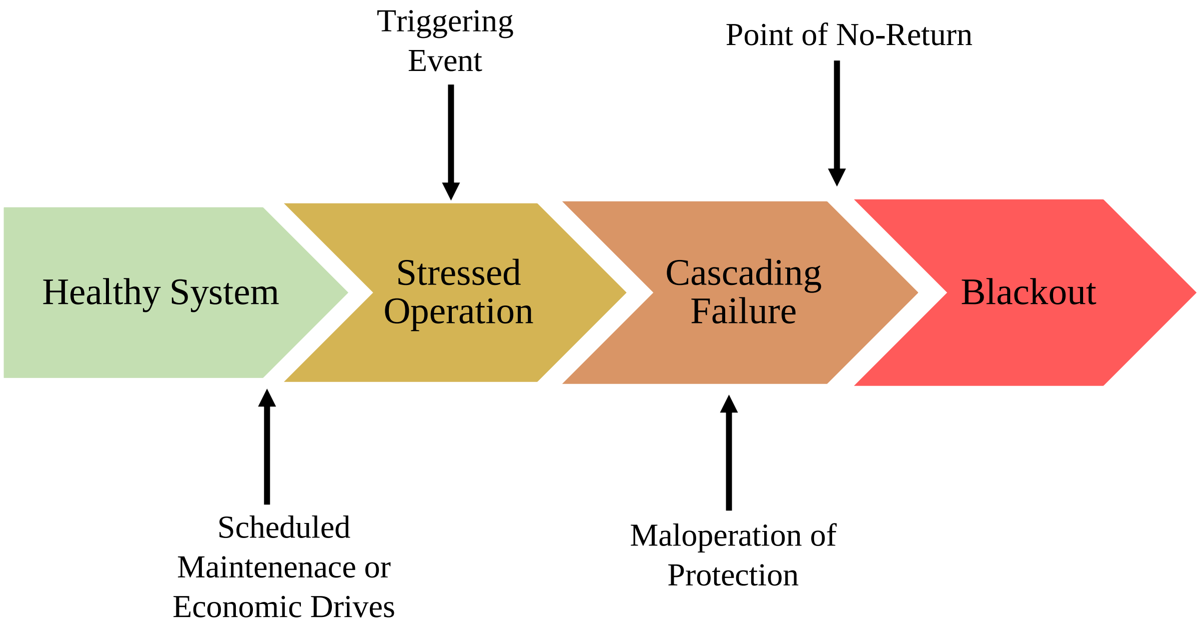


Figure II.1. A generalized blackout pattern

## II.3 Load Shedding Techniques

Load shedding is a critical technique used to prevent power systems from collapsing during periods of high demand or unexpected events such as equipment failure or extreme weather conditions. When the demand for power exceeds the capacity of the system, the voltage and frequency of the power system can become unstable, leading to power outages and blackouts. Load shedding techniques are designed to maintain the stability of the power system by selectively disconnecting certain loads [1, 3].

### II.3.1 Under Voltage Load Shedding

Under Voltage Load Shedding (UVLS) is a protective measure that is widely used in power systems to maintain system stability and prevent voltage collapse. Voltage collapse occurs when the voltage in a power system drops below a critical level, which can result in a loss of synchronization and cascading failures throughout the system [3].

To prevent voltage collapse, UVLS is designed to automatically shed a pre-determined amount of load from the system in response to a voltage drop below a set threshold [2]. The amount of load that is shed is typically determined based on the size and importance of the connected loads, with less critical loads being disconnected first [3].

UVLS can be implemented using a variety of protective relays, including under voltage relays, overcurrent relays, and frequency relays. These relays monitor the voltage, current, and frequency of the system and activate the load shedding process when necessary [2, 3].

One of the main challenges associated with UVLS is determining the optimal voltage threshold and load shedding strategy to ensure system stability while minimizing the impact on customers. The voltage threshold must be set low enough to prevent voltage collapse, but high enough to avoid unnecessary load shedding that can cause customer discomfort or equipment damage.

Another challenge with UVLS is that it can result in imbalances in the system, leading to frequency variations and other issues. To address these challenges, researchers are exploring new techniques for load shedding that can adapt to changing system conditions and maintain voltage stability while minimizing the impact on customers [3].

Overall, under-voltage load shedding is an essential protective measure for ensuring the safe and stable operation of power systems. However, it is important to carefully design and implement UVLS to ensure that it is effective at maintaining system stability while minimizing the impact on customers and equipment.

### II.3.2 Under Frequency Load Shedding

Under Frequency Load Shedding (UFLS) is a protective scheme used in power systems to maintain stability by preventing widespread blackouts. It is activated when the frequency of the power system drops below a certain threshold, which can occur due to a sudden increase in demand or a loss of generation capacity [17].

The UFLS technique has been in use since the 1930s and has proven to be an effective method for preventing widespread blackouts [17]. The basic principle behind UFLS is to disconnect a predetermined amount of load when the frequency of the power system drops below a certain level, which helps prevent generators from tripping and causing a complete blackout [18].

UFLS is usually implemented using protective relays that monitor the frequency of the power system and activate the load shedding process when necessary. The amount of load shed is typically based on the size of the frequency deviation and the available generation capacity.

UFLS is usually designed to shed a predetermined amount of load based on the frequency deviation [21].

Although UFLS is an effective technique for maintaining the stability of power systems, it can have some negative effects on the quality of power supplied to the remaining loads. When loads are disconnected from the system, it can cause voltage fluctuations that can damage sensitive equipment. Additionally, UFLS can be expensive to implement as specialized protective relays are required [18].

## II.4 Features and Issues of Under Frequency Load Shedding

Under Frequency Load Shedding (UFLS) is a critical measure to prevent frequency declines in power systems during serious disturbances. Its main objective is to maintain power balance and stabilize frequency. Here are the key features that UFLS schemes should provide, as outlined in [17]:

- Minimal time for the frequency to return to its nominal value,
- Reliable and redundant protection to avoid malfunctions that can lead to system failure,
- Minimal load shedding amount, but sufficient to restore the frequency to its nominal value,
- Low cost of UFLS action.

Operating at low frequency in power systems can result in two main issues. The first issue is the vibratory stress on the long low-pressure turbine blades, which are designed to operate at frequencies above 47.5 Hz for countries that use a 50 Hz frequency standard. This stress accumulates with time, underscoring the need to restore the frequency to its nominal value as quickly as possible [17].

The second issue is related to the performance of plant auxiliaries driven by induction motors. At low frequencies, the capability of plants can be reduced due to decreased output of boiler feed pumps or fans that supply combustion air [18].

Therefore, an efficient UFLS scheme that prioritizes the key features outlined above is essential for maintaining frequency stability and avoiding the negative impacts associated with low-frequency operation in power systems [19].

## II.5 Under Frequency Load Shedding Techniques

At the time of a disturbance that causes power imbalance between generation and load, it is impossible to know the exact amount of overloading and load shedding required to restore the frequency to its nominal value. To prevent power system blackouts, several types of under frequency load shedding (UFLS) techniques have been developed and categorized into five groups: conventional, adaptive, semi-adaptive, computational-based, and WAMS (Wide Area Measurement System) based UFLS techniques, as shown in Figure II.2.

UFLS schemes are typically grouped into two categories: static (fixed) and dynamic (adaptive). Traditional schemes are a type of static UFLS scheme that sheds a predetermined amount of load when the frequency falls below a defined threshold. However, this initial load shedding may not be enough to increase the frequency and stabilize the system, so the process may need to be repeated until the frequency stabilizes. The threshold and load shedding amounts are determined based on experience and simulations. To avoid over-shedding, it is recommended that load be shed in a few stages, with moderate amounts shed at each stage [20].

Semi-adaptive load shedding schemes are based on the rate of decline in frequency as a measure of the generation shortage. The amount of load to shed, thresholds, and rate of change of frequency are decided based on experience and simulations [21].

Adaptive load shedding schemes consider various parameters of the system to make decisions about the size of the load to shed, frequency threshold, and rate of change of frequency (ROCOF). These schemes are dynamic and adjust the load shedding amounts and thresholds based on the system conditions. The most common adaptive techniques are event-based, response-based, and techniques based on frequency prediction [24].

ROCOF-based UFLS schemes are classified under adaptive schemes, but are generally semi-adaptive. Computational techniques are based on intelligent algorithms, such as Artificial Neural Networks (ANN), Fuzzy Logic Control (FLC), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Genetic Algorithms (GA), and Particle Swarm Optimization techniques (PSO) [20].

WAMS-based UFLS techniques are generally adaptive techniques with real-time monitoring, control, and protection of large power systems covering a large geographical area [26].

Figure II.2 presents the classification of UFLS techniques in diagrammatic form. In the following, these techniques are comprehensively surveyed considering their practical challenges [21, 23].

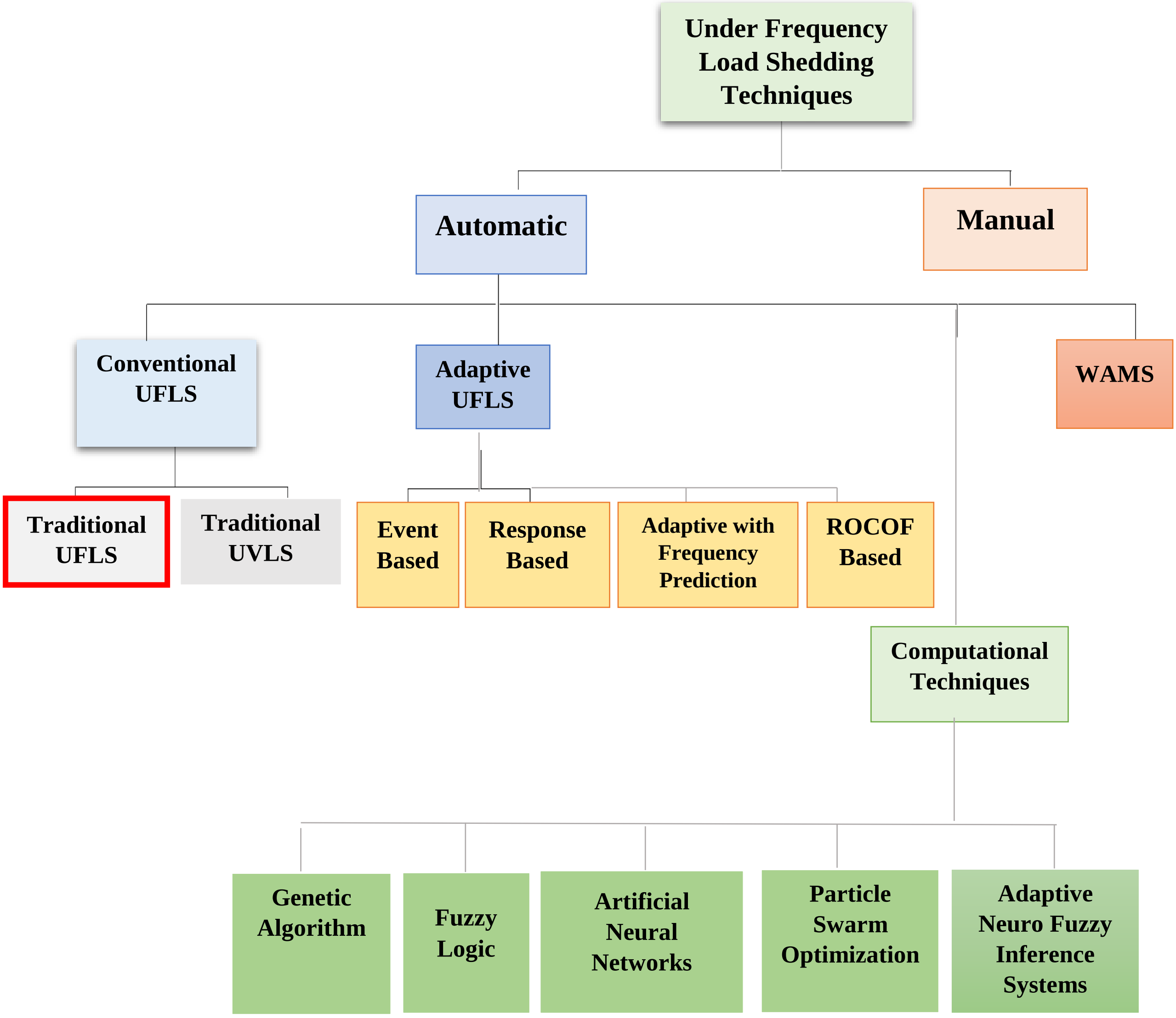


Figure II.2. Load shedding techniques [21, 23]

### II.5.1 Conventional and Traditional UFLS

Conventional under frequency load shedding (UFLS) techniques encompass various traditional methods to prevent power system frequency from falling below a specified threshold. Figure II.3 provides an overview of the operation of the most prevalent types of conventional UFLS. Whenever a frequency threshold is violated, a specific amount of load is shed without considering the severity of the disturbance [23].

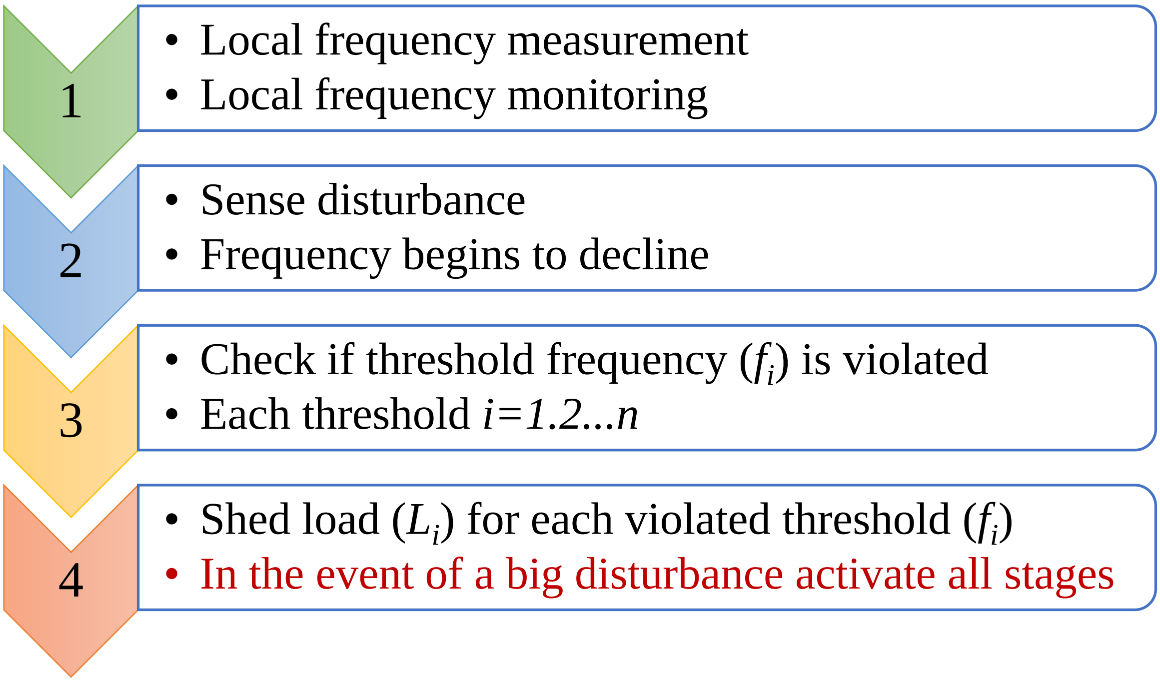


Figure II.3. Summary of conventional UFLS

Traditional UFLS is considered as the most common method and forms the basis of all other UFLS techniques [23]. In this method, relays make use of locally measured frequency, which is constantly compared against a number of certain thresholds, which may differ from one power system to another.

Violation of any threshold triggers a relay action [24]. For a 50Hz system most manufacturers specify 47.5Hz as the minimum frequency threshold, because this is the frequency limit below which turbines cannot operate efficiently [25, 26]. The European Network of Transmission System Operators for Electricity (ENTSO-E) recommends that UFLS must be initiated at 49Hz, at which 5% of the total load must be shed and by the time frequency reaches 48Hz, 50% of the total load must have been shed in successive steps [27]. A typical UFLS scheme according to ENTSO-E requirements is shown in Table II.1.

**Table II.1** A typical conventional UFLS scheme for ENTSOE

| ***Frequency Threshold (Hz)*** | *49* | *48.8* | *48.6* | *48.4* | *48.2* | *48* |
|---|---|---|---|---|---|---|
| ***Load-shed (%)*** | *5* | *5* | *10* | *10* | *10* | *10* |

At 49Hz, a 5% of the total load is shed and another 5% is shed, when frequency reaches 48.8Hz. If the frequency continues to drop, 10% of the load is shed whenever a threshold is violated. In order to provide a visual understating of traditional schemes, the percentage of load shed is plotted for each frequency threshold during the frequency decline for ENTSO-E system as shown in Figure II.4.

To come up with thresholds as in Table II.1, the system history and the experiences of the operator are considered, supported by several simulations of the system frequency response (SFR) to evaluate the system frequency response in the event of a critical system contingency are performed. Each system has its own shedding frequency thresholds based on its capacity, inertia, reserve and other conditions [28].

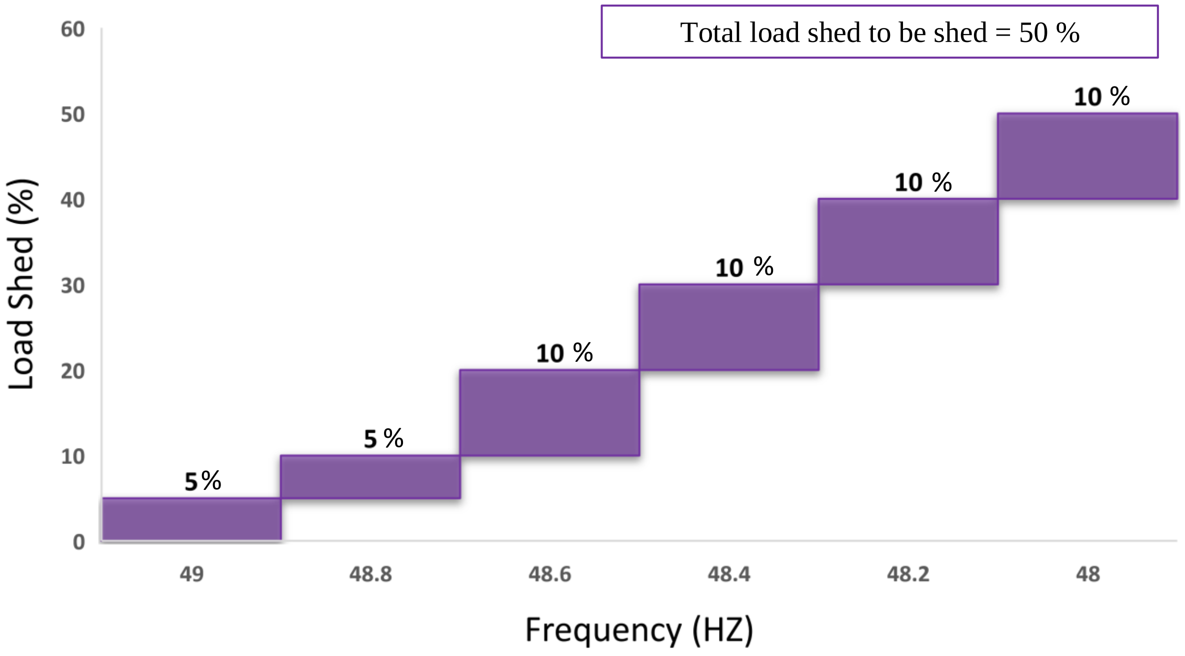


Figure II.4. A typical conventional UFLS scheme for ENTSOE which is 50 Hz system; (frequency vs. load to be shed)

There are various conventional UFLS methods that have been proposed in previous studies to ensure the stability and security of power systems during emergencies. These methods are designed to shed load in a systematic and controlled manner when the frequency of the power system drops below a certain threshold, which can cause the system to become unstable.

One such method is an 8-stage UFLS plan that was designed in [29]. In this plan, load shedding is initiated at 49.5Hz, and at the eighth stage, load 8 is shed at 48.5Hz. Another approach is presented in [28], where 60% of the load is shed starting at 49.1Hz, up to the minimum frequency of 47.5Hz.

In [30], a three-stage UFLS plan is proposed, where load shedding is initiated at 59.2Hz, and the load is shed in increments of 10%, 15%, and 20% at 58.8Hz, and 58.0Hz, respectively.

Similarly, in [31], a traditional UFLS scheme is presented, where 80% of the load is shed in 20 stages starting at 48.5Hz up to 46.5Hz, with consecutive stages of 0.1Hz steps.

To minimize the number of steps and reduce the overlapping effects, a reduced step UFLS method is proposed in [32], where the initial load shedding frequency is set to 49.2Hz, and the last is 48.4Hz.

In [33], a six stage traditional UFLS scheme is proposed for American Electric Power System, which serves seven states and is conformed to East Central Area Reliability Agreement (ECAR) standards. The threshold shedding frequencies are 59.9Hz, 59.4Hz, 59.3Hz, 59.1Hz, 59.0Hz and 58.9Hz at which 3.33%, 3.33%, 3.33%, 5%, 5% and 5% of the total load is shed, respectively. Figure II.5 shows a visual representation of this transnational UFLS scheme in USA in which the percentage of load shed is plotted for each frequency threshold. This system is a 60 Hz frequency system.

UFLS schemes applied in different continents/countries show differences in the total load to be shed, number of UFLS stages, percentage of load to be shed at each stage, and the set frequency threshold. These differences are due to the differences in system size, systems total inertia, and the generation mix. In [34, 35], different settings for traditional under frequency load shedding are shown.

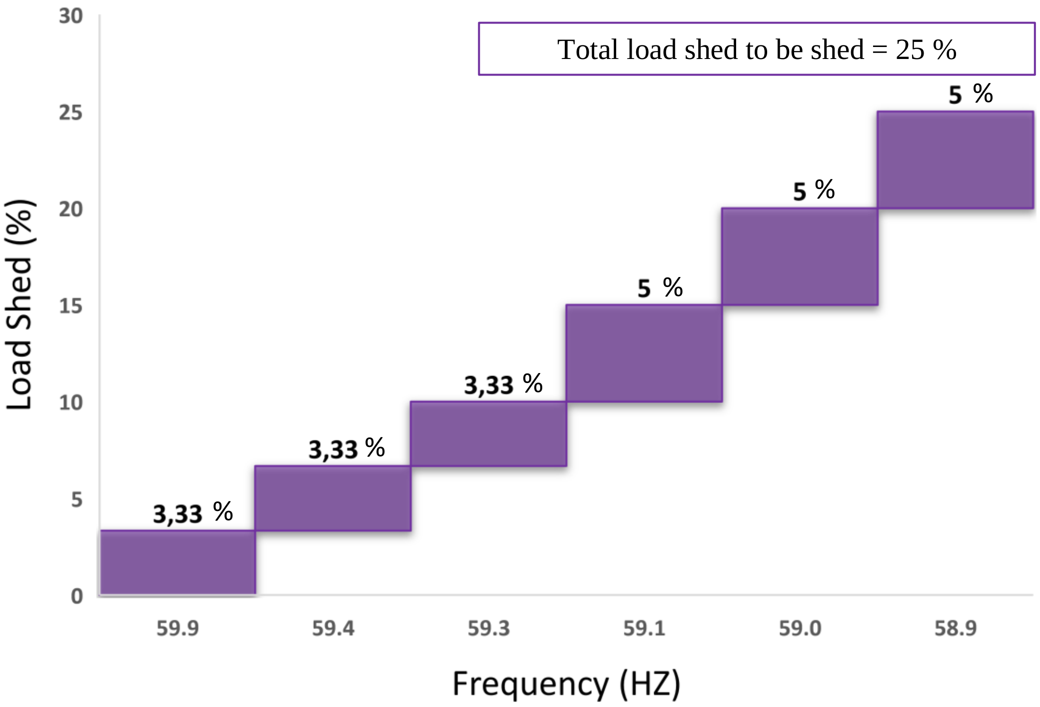


Figure II.5. A typical conventional UFLS scheme for American Electric Power System

The main advantages of conventional UFLS technique are [38, 39]:

- Simplicity: The conventional UFLS technique is relatively simple and straightforward, making it easy to understand and implement. The approach relies on pre-defined frequency thresholds that trigger load shedding actions, which can be programmed into protective relays. This simplicity makes it a practical solution for many power systems and reduces the risk of errors or complications during implementation.
- Versatility: The conventional UFLS technique can be applied to any power system, regardless of its size or complexity. This means that it can be used in both small and large-scale systems, and can be customized to suit the specific needs and requirements of each system. This versatility also means that the conventional UFLS technique can be easily modified or upgraded to incorporate new technologies or features.
- Backbone of modern UFLS techniques: The conventional UFLS technique forms the foundation for more modern and advanced UFLS techniques. By using locally measured frequency and pre-defined thresholds, the conventional technique provides a reliable and efficient way to shed load and stabilize the system during frequency drops. This approach has inspired the development of newer UFLS techniques that use more sophisticated algorithms, advanced sensors, and other advanced technologies to further enhance system performance.
- Proven efficiency: Despite being a relatively simple technique, conventional UFLS has been shown to be highly effective in maintaining system stability during frequency drops. By shedding load at specific frequency thresholds, the technique helps to prevent system collapse and avoid potential blackouts. The technique has been used for many years in power systems around the world and has a proven track record of success, making it a reliable and effective method for managing frequency stability.

Despite their simplicity, they also present several disadvantages, as follows:

- Constant amount of load shedding: The conventional UFLS technique sheds a constant amount of load at each frequency threshold, regardless of the severity or type of disturbance. This can lead to inefficient use of resources and may not be effective for all types of system disturbances.
- Fixed frequency thresholds: The frequency thresholds used in conventional UFLS are fixed and cannot be adjusted in real-time. This means that the system may not be able to respond quickly or effectively to sudden changes in frequency or system conditions.

- Same load shedding locations: If shedding by priority is used, the same locations of loads are shed at each step and time, which can result in imbalanced load shedding and may negatively impact system stability.
- Same delay for all events: The conventional UFLS technique typically has the same delay for all events, which may not be appropriate for all types of system disturbances and may result in inefficient or ineffective load shedding.
- Lack of generation-demand deficit calculation: The conventional UFLS technique does not take into account the generation-demand deficit, which can result in over-shedding or under-shedding, both of which can negatively impact power quality and system stability.
- Negative impact on voltage stability [36]: In some cases, the conventional UFLS technique may negatively impact voltage stability, which can lead to further system instability and potential blackouts.
- Insensitivity to frequency gradient: The conventional UFLS technique may treat steep and gradual changes in frequency gradient similarly, which can result in over or under-load shedding, and may not be an effective approach for managing system stability.

## II.6 Important Parameters For Under Frequency Load Shedding

When designing UFLS schemes, there are different factors that have to be taken into consideration in order to create a good and effective scheme. These are the main factors [22]:

- Minimum allowable frequency for secure system operation,
- The amount of load to be shed,
- Different frequency thresholds,
- The number of UFLS steps and their sizes,
- Time delays.

Many parts of the system have different minimum operable frequencies. For example, generators must not operate at frequencies below 47.5 Hz, as the turbine blades will experience damaging oscillations. Therefore, it is very important to consider the minimum allowable frequency for secure system operation when designing the UFLS scheme [28].

The amount of load to be shed has to be carefully decided. It is not good to shed too little load because it will cause the frequency to continue to drop and it can lead to the instability of the system and its complete collapse. If we shed too much load, it can cause over-shedding, which should be avoided as well [23].

Each scheme will have a different threshold, and the threshold should never be too close to the nominal frequency. The frequency threshold is usually one of the parameters that trigger the UFLS scheme, and if it is too close to the nominal value, then the scheme will activate even for small frequency swings that cannot harm the system. At the same time, the threshold should not be too close to the minimum operable frequency because some time should be allocated for UFLS to act [22].

The number of load shedding steps and the size of each one are important factors that affect the UFLS scheme. The UFLS steps should be far enough from each other to avoid overlap of load shedding due to time delays. That means if the steps are too close to each other, the second step could start before the first one has finished, causing over-shedding. Too close steps could also cause the second step to start before the system inertia has responded to the previous step. This brings us to the conclusion that the scheme should have more steps rather than fewer, and the steps should be distributed across the system. By having more steps, the frequency would gradually recover, avoiding unnecessary shedding and minimizing the cost of load shedding.

The last on the list, but not less important, is the time delay. Time delay has to be introduced to accommodate the response time of the system to each of the steps of load shedding and to ride out short time transient frequency excursions. In the case of too large time delay, the frequency can continue to drop, resulting in a failure of the system.

Each of the mentioned parameters is important to consider when designing and implementing the UFLS scheme, and they are used as a basis for the UFLS scheme assessment.

## II.7 Impact of Distributed Generation and New Technologies on UFLS

The deployment of distributed generating units at Medium Voltage (MV) and Low Voltage (LV) levels has brought about significant changes to the power system, including the generation, distribution, and consumption of electricity. These changes have introduced new challenges for conventional multi-stage UFLS (Under Frequency Load Shedding) schemes, which were originally designed for traditional power systems dominated by large central power plants [37].

One of the key challenges posed by the integration of distributed generators and loads is the increased uncertainties in the effective parameters of power systems, such as total rotating inertia and load damping coefficient [37]. These parameters play a crucial role in the frequency response of the power system during contingency events, as they determine how quickly the frequency changes in response to variations in power demand or supply.

The integration of various types of distributed generators and loads, such as wind turbines, solar photovoltaic panels, and battery energy storage systems, has significantly altered the effective parameters of power systems. For instance, unlike traditional power plants, wind turbines and solar photovoltaic panels lack rotating masses, resulting in a reduced contribution to the total rotating inertia. This can lead to faster frequency responses during contingency events, potentially causing instability in the power system if not adequately managed. Similarly, battery energy storage systems have the capability to absorb or inject power into the grid, affecting the load damping coefficient and influencing the frequency response of the power system [19].

Overall, the integration of distributed generators and loads has amplified the uncertainties in the effective parameters of power systems, presenting new challenges for UFLS schemes. To effectively address these challenges, new control strategies and technologies must be developed to ensure the stability and reliability of the power system in the face of evolving power demand and supply dynamics. By leveraging innovative approaches, it becomes possible to adapt UFLS schemes to the changing power system landscape and maintain a resilient power grid [37].

## II.8 Chapter Conclusion

In conclusion, this chapter has discussed the importance of under frequency load shedding (UFLS) as an emergency control action in the case of power system imbalance. We have seen that every power system has its own emergency control plan, which can be either static or dynamic, depending on its flexibility.

We have also explored different load shedding techniques and important parameters for UFLS, such as frequency sensitivity, load shedding priority, and load shedding sequence. These parameters play a crucial role in ensuring that the load shedding process is efficient and effective.

Furthermore, we have discussed the impact of distributed generation and new technologies on UFLS. With the increasing use of renewable energy sources and distributed generation, power systems are becoming more complex, and traditional UFLS techniques may not be sufficient.

Overall, this chapter has provided a comprehensive overview of UFLS and its importance in maintaining power system stability. It is clear that UFLS is a critical emergency control action that must be carefully designed and implemented to ensure the reliable and secure operation of power systems.

# Chapter III

## *UFLS Simulation with ETAP: Analysis & Results*

## III.1 Chapter Introduction

In this chapter, we investigate an Under Frequency Load Shedding (UFLS) plan to restore system frequency during severe generation outages. The integration of Renewable Energy Sources (RESs) through inverter technology offers numerous benefits, but it can also reduce the power system's inertia, leading to frequency stability issues. Our study focuses on evaluating the effectiveness of the proposed UFLS plan on the IEEE 39-bus system, which is widely used as a benchmark for power system studies.

To assess the performance of our proposed UFLS plan, we employ the Electrical Transient Analyzer Programme (ETAP Software) to simulate the behavior of the tested system under various scenarios.

## III.2 ETAP Software

Electrical Transient Analyzer Program (ETAP) is a full spectrum analytical engineering software developed by Operation Technology Inc. (OTI). The software specializing in the analysis, simulation, monitoring, control, optimization, and automation of electrical power systems. ETAP software offers the most comprehensive and integrated suite of power system enterprise solution that spans from modeling to operation [42].

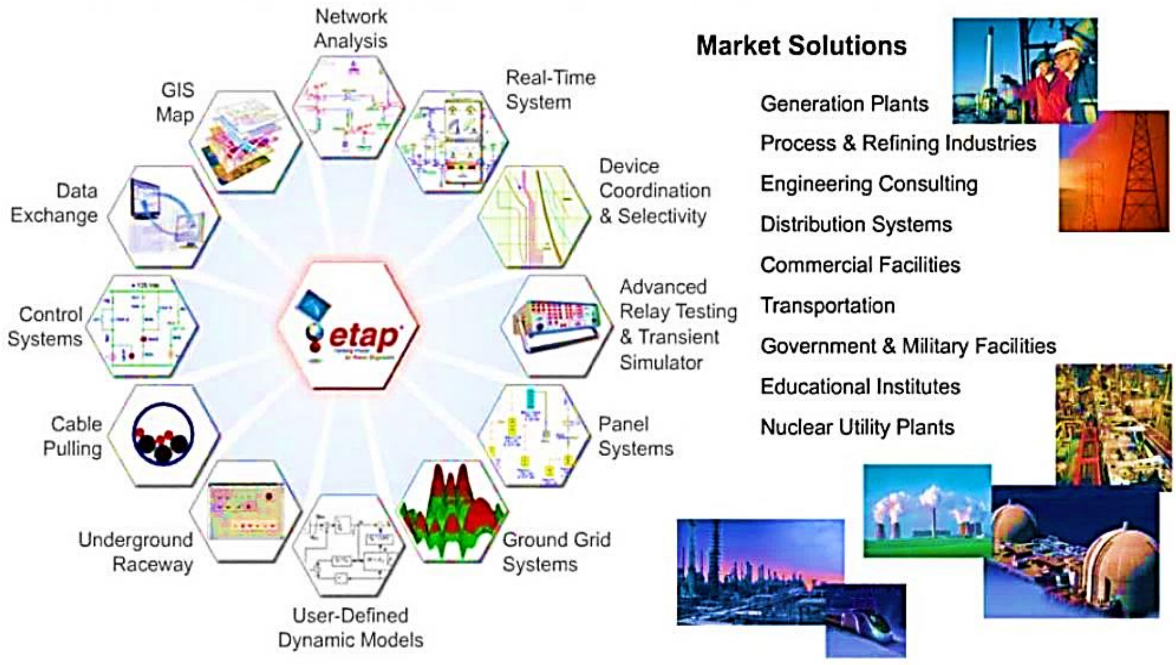
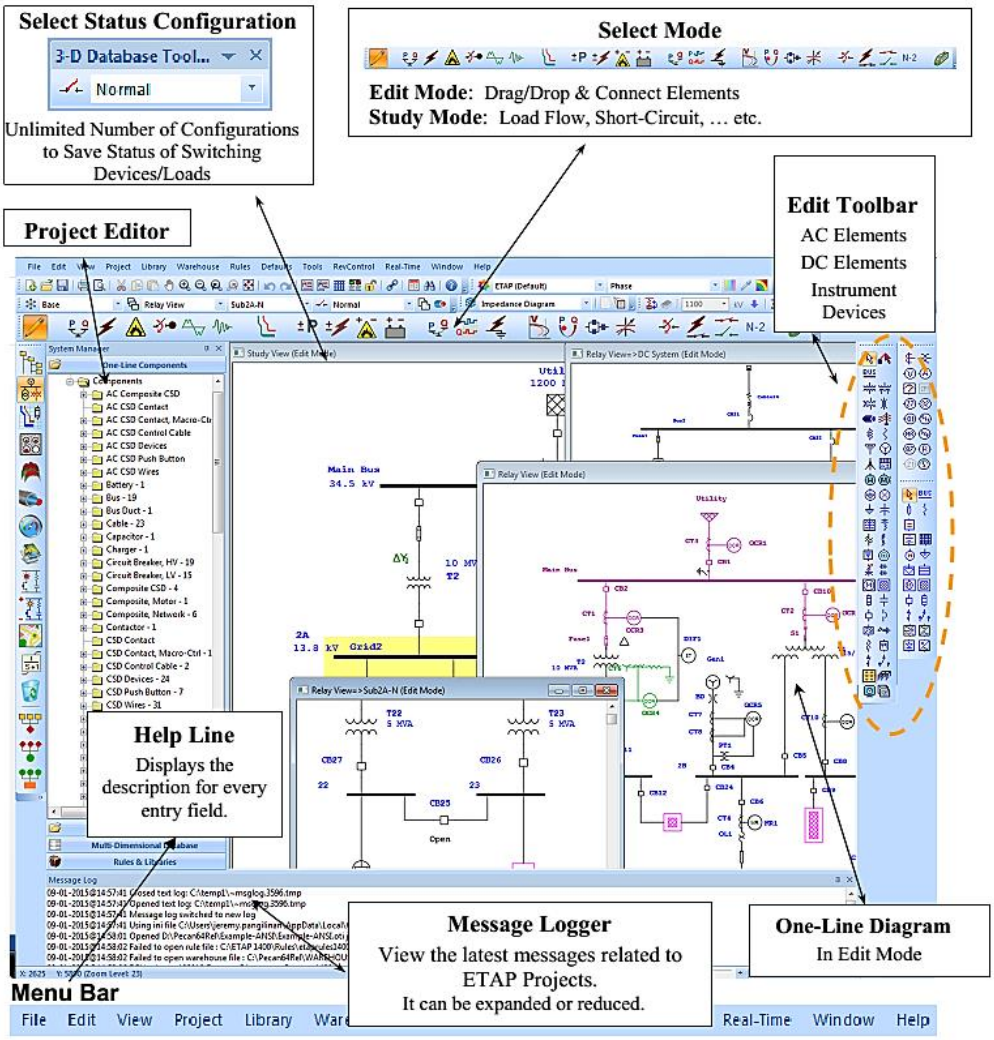


Figure III.1. ETAP features overview [42]

The ETAP Software provides a good interface for performing rigorous analysis on electrical power systems and is one of the best in Electrical Transient analysis softwares. It’s integration to Microsoft Excel is also one of its many amazing features.

The ETAP Software provides an easy to use, user friendly environment along with a comprehensive user manual that helps user through any problem encountered during simulation. The Basic interface of ETAP is shown in figure below [42].



Unlimited Number of Configurations to Save Status of Switching Devices/Loads

**Edit Mode:** Drag/Drop & Connect Elements
**Study Mode:** Load Flow, Short-Circuit, … etc.

Displays the description for every entry field.

View the latest messages related to ETAP Projects.
It can be expanded or reduced.

Figure III.2. ETAP GUI based user Interface [42]

### III.2.1 ETAP Toolbars

ETAP software is intelligently divided into different toolbars according to their functionality. User can easily access each toolbar while creating one line diagram of a power system model. Besides toolbars, there are different options available to perform analyses on the system model through study cases, configurations, edit toolbars.

Mode toolbar is located on top of GUI just below the file menu. Different Analysis Modes can be selected from this Mode Toolbar according to the requirement of the project.

In ETAP, a complete set of analyses has been provided through the mode toolbar as given in the list below:

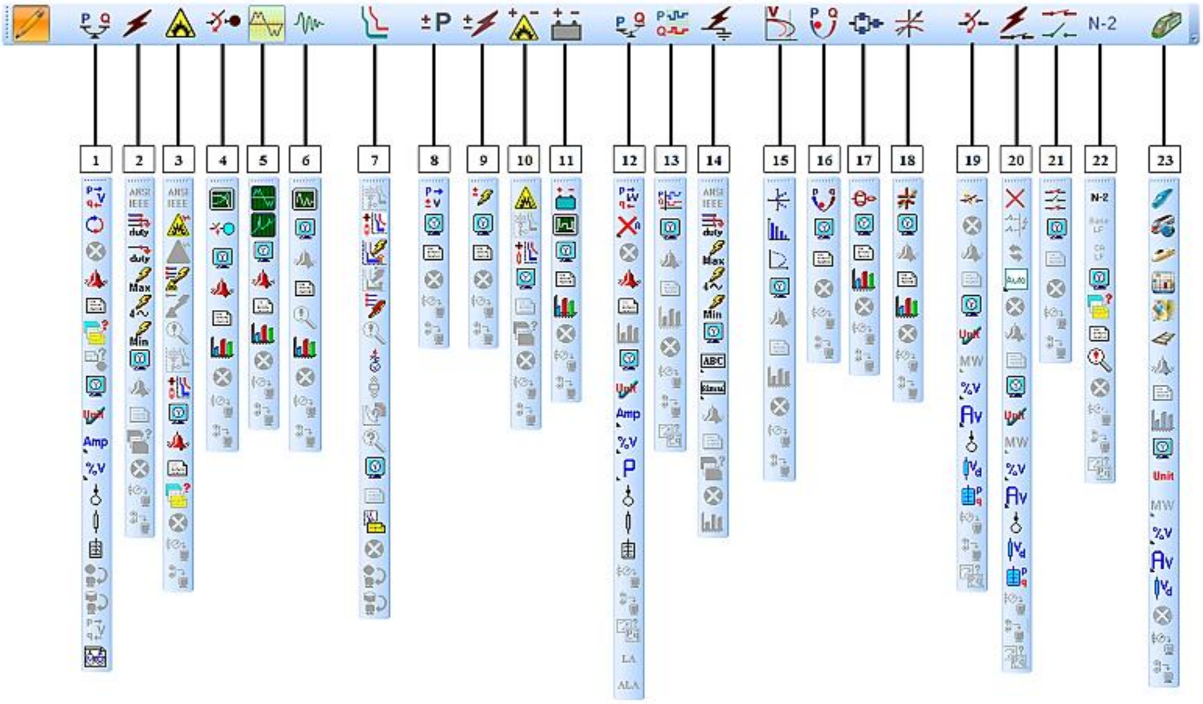


Figure III.3. ETAP Mode toolbars for various power system analyses [42]

There are total 23 study modes in ETAP as depicted in Figure III.3. Each one of them is briefly described in the order from left to right [42]:

1. Load Flow Analysis
2. Short-Circuit Analysis
3. Arc Flash Analysis
4. Motor Acceleration Analysis
5. Harmonic Analysis
6. Transient Stability Analysis
7. Star – Protective Device Coordination
8. DC Load Flow Analysis
9. DC Short-Circuit Analysis
10. DC Arc Flash Analysis
11. Battery Sizing and Discharge Calculations
12. Unbalanced Load Flow Analysis
13. Time Domain Load Flow Analysis
14. Unbalanced Short Circuit Analysis
15. Voltage Stability Analysis
16. Optimal Power Flow Analysis
17. Reliability Assessment
18. Optimal Capacitor Placement
19. Switching Optimization
20. FMSR Analysis
21. Switching Sequence Management
22. Contingency Analysis
23. Rail Traction Power

### III.2.2 ETAP's Transient Stability Analysis

ETAP's Transient Stability Analysis module is a powerful tool for studying the dynamic behavior of power systems during disturbances or changes. The module models the dynamic characteristics of the power system, solving equations interactively and analyzing responses in the time domain. It provides a detailed analysis of the system's transient response, allowing users to assess system stability, set protective device settings, and implement necessary enhancements. Figure III.4 represents transient stability analysis mode in ETAP.

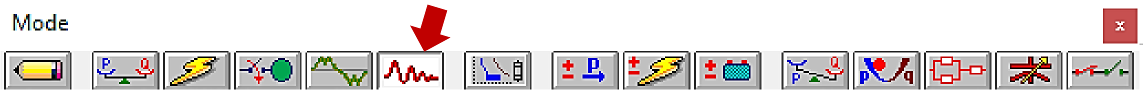


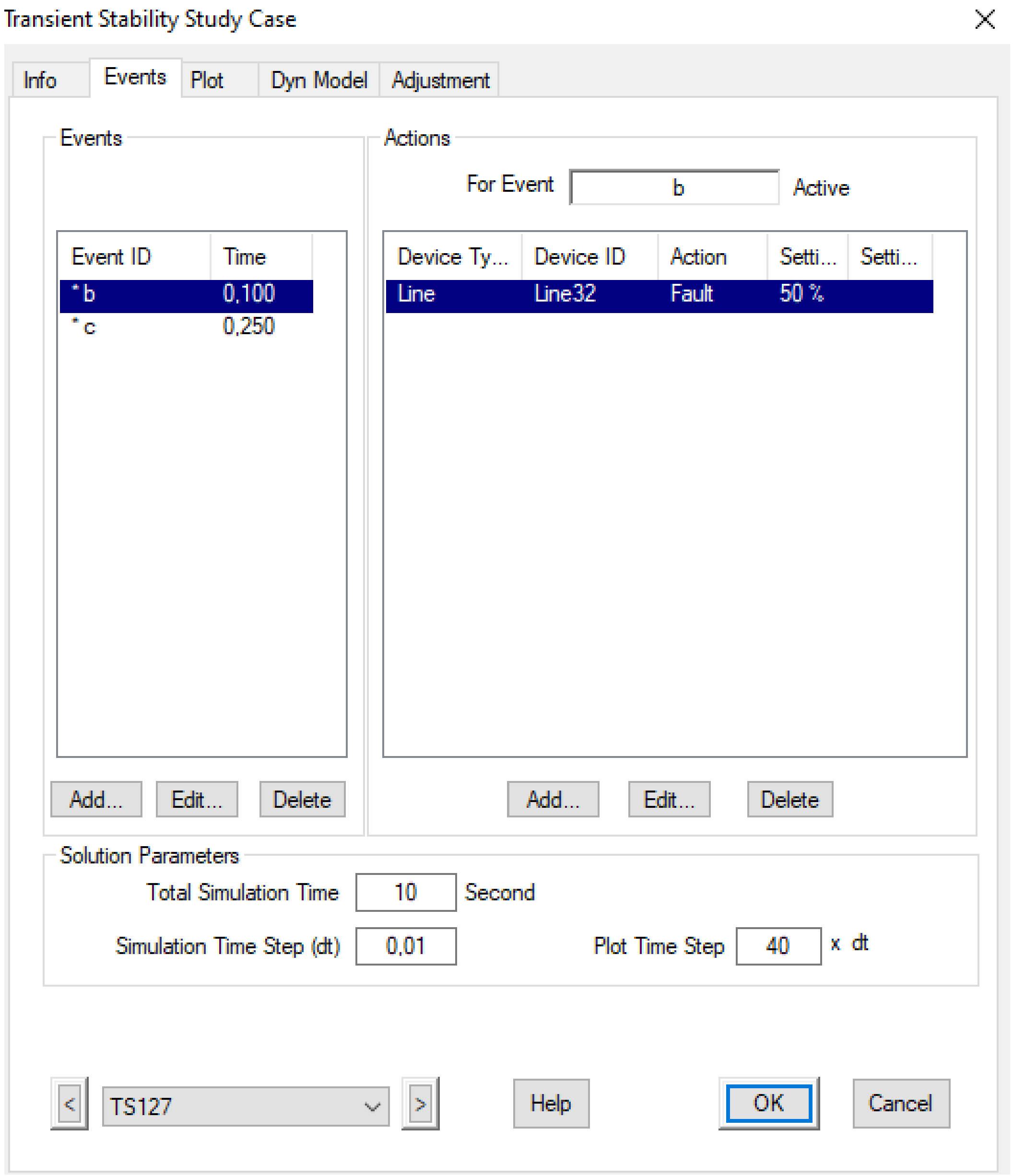
Figure III.4 Transient stability analysis mode

The ETAP transient stability study case editor provides a comprehensive approach to analyze and investigate the dynamic responses and stability limits of a power system during changes or disturbances. It allows users to model the dynamic characteristics of the power system, solve equations interactively, and analyze responses in the time domain. With the editor's user-friendly interface, users can easily specify the system components, settings, and events, making it a versatile tool for power system analysis. The transient stability study case editor in ETAP offers a broad range of modeling capabilities, including generators, motors, loads, transformers, transmission lines, circuit breakers, and relays. Users can add, modify, or delete both events and actions within these events, allowing for extensive customization and detailed analysis [42].

Figure III.5 illustrates the transient stability study case editor in ETAP used in our study case, which demonstrates two events that have been entered, Event 1 and Event 2. Event 1 represents a fault occurring at time t=0.1 seconds, and Event 2 represents the circuit breakers opening at time t=0.25 seconds. The editor provides the flexibility to change these events and actions, modify settings, and analyze simulation results graphically, making it an essential tool for transient stability analysis in power systems .One of the significant benefits of ETAP's transient stability analysis module is that it can simulate large power systems with complex control and protection schemes. The module can model the system's nonlinear behavior, including voltage and frequency instability, generator outages, and other types of disturbances. The module also considers the effects of system damping, governor action, and excitation control on the system's dynamic behavior.

ETAP's Transient Stability Analysis module also provides several analysis tools to assess system stability, including power-angle curves, time-domain simulation, and frequency-domain analysis. These tools allow users to evaluate the system's stability limits, identify critical components, and optimize protective device settings to ensure system stability during disturbances.

Overall, ETAP's transient stability analysis module is a comprehensive tool for studying power system dynamics during transient events. Its graphical user interface, modeling capabilities, and analysis tools make it a powerful solution for power system engineers and operators to ensure the stability and reliability of their systems [42].



| Event ID | Time |
|---|---|
| * b | 0,100 |
| * c | 0,250 |

For Event: b — Active

| Device Ty... | Device ID | Action | Setti... | Setti... |
|---|---|---|---|---|
| Line | Line32 | Fault | 50 % | |

Total Simulation Time: 10 Second

Simulation Time Step (dt): 0,01

Plot Time Step: 40 x dt

TS127

Figure III.5. Transient stability case study editor

### III.2.3 Frequency Relay

In power systems, frequency relays are essential components of protection schemes, and their properties can be specified in the frequency relay editor in ETAP software. These relays are similar to voltage relays and can be used in transient stability studies, where the circuit breaker control interlock functions and settings are specified. The transient stability program will monitor system quantities and compare them with the relay settings. If the control conditions are met, the associated control actions will be triggered. To ensure accurate voltage and frequency measurement, frequency relays should be connected to a bus via a potential transformer [42]. Figure III.6 displays the device 81 relay symbol, which is typically used to represent frequency relays in the one-line diagram.

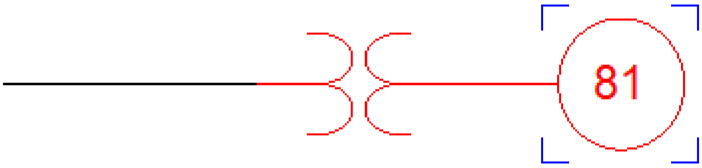
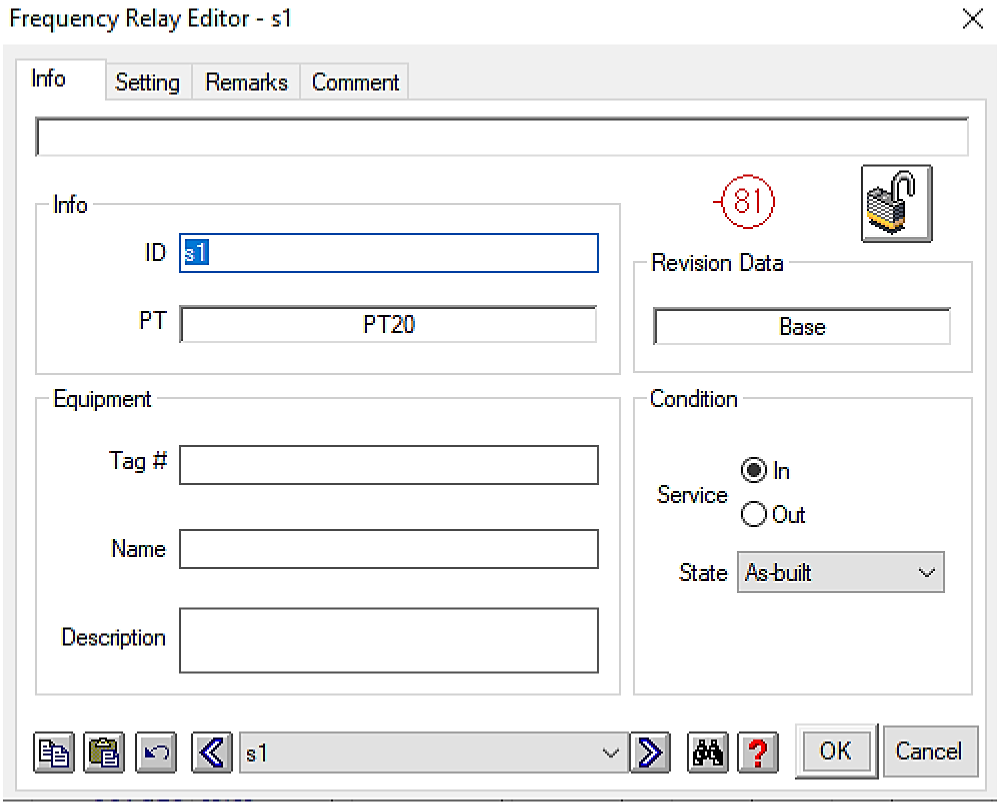


Figure III.6. Device 81 relay symbol

The frequency relay editor in ETAP software contains several pages of information, including the info page (Figure III.7), which displays general information about the relay.


Frequency Relay Editor - s1

Info

ID: s1

PT: PT20

Revision Data: Base

Equipment

Tag #:

Name:

Description:

Condition

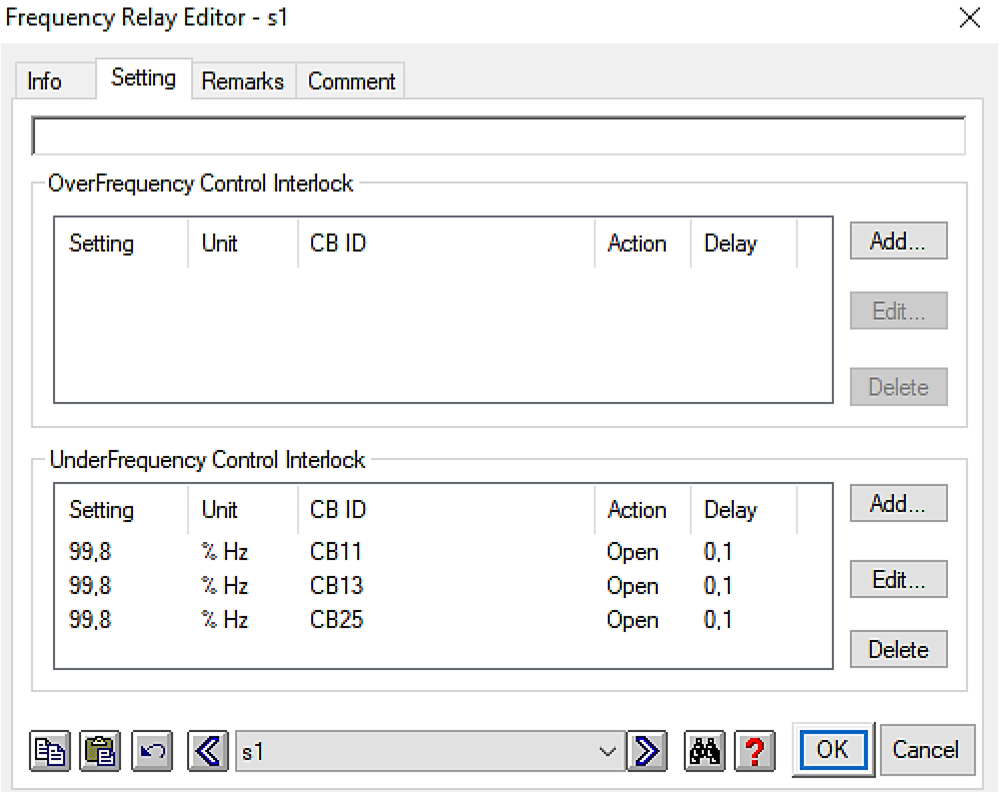
Service: ● In ○ Out

State: As-built

s1

Figure III.7. The frequency relay editor (Info Page)

The setting page allows users to configure the relay's settings for different events, such as under-frequency or over frequency events. Figure III.8 provides an example of the setting page for an under frequency event in the first stage of scheme 2 used in our study case.



OverFrequency Control Interlock

| Setting | Unit | CB ID | Action | Delay |
|---|---|---|---|---|

UnderFrequency Control Interlock

| Setting | Unit | CB ID | Action | Delay |
|---|---|---|---|---|
| 99,8 | % Hz | CB11 | Open | 0,1 |
| 99,8 | % Hz | CB13 | Open | 0,1 |
| 99,8 | % Hz | CB25 | Open | 0,1 |

Figure III.8. The frequency relay editor (The Setting Page)

In addition, the frequency relay editor also includes the remarks page and comment page. The remarks page in the frequency relay editor of ETAP software allows users to add notes and comments about the relay settings, such as the reason for selecting a certain setting or the expected behavior of the relay during a specific event. This information can be helpful for other engineers who may be working on the same project in the future or for users who need to revisit the relay settings at a later time. The comment page, on the other hand, allows users to add general comments about the frequency relay. This could include information about the device, such as the manufacturer or model number, or notes about its location or function within the power system. These comments can provide additional context and help ensure that everyone involved in the project is on the same page [42].

Overall, the use of frequency relays and ETAP software in transient stability studies is crucial in maintaining the stability and protection of power systems.

# III.3. Modelling Overview

## III.3.1 Test Power System

The 10-machines (60Hz) 39- standard system is a power network in the New England area of the United States, this system is widely used for power system dynamic stability studies. The system consists of 10 generators, 39 bus bars and 12 transformers. The test system data is given in Appendix A.

The UFLS schemes are implemented in the IEEE 39-bus test system, as shown in Figure III.9. During the implementation, various system separation scenarios are created to form islands with generation deficiency.

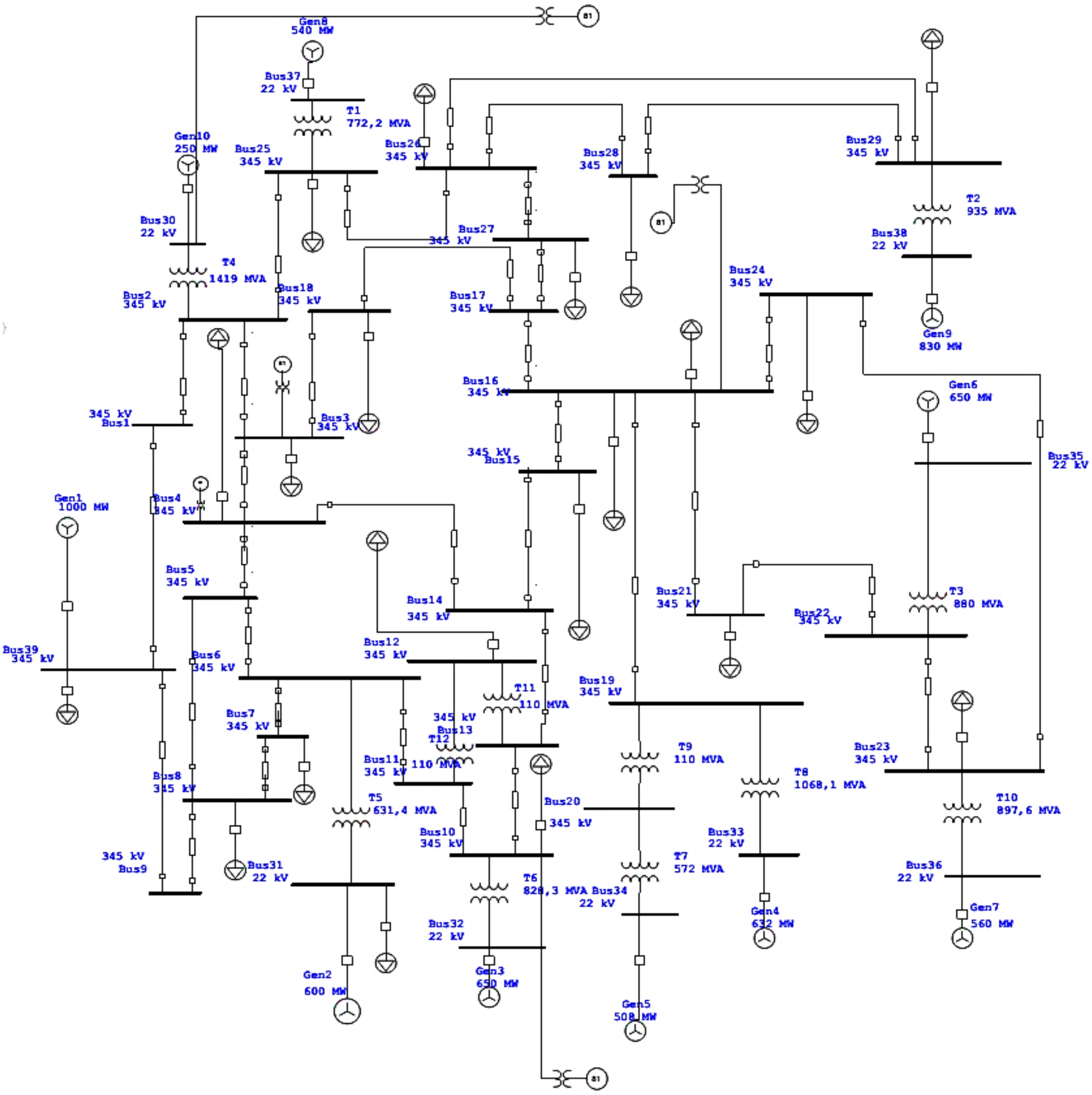


Figure III.9. Single-line diagram of the IEEE 39-bus test system

### III.3.1.1 Load Flow Results

Load flow analysis was performed using ETAP software to determine the steady-state operating conditions of the tested system. The results are in Table III.1. For a more complete description of power flow, including flow on each line, see the Appendix B.

**Table III.1** Power flow results

| *Bus ID* | *Nominal kV* | *Type* | *Voltage (%)* | *MW Loading* | *Mvar Loading* |
|---|---|---|---|---|---|
| *Bus1* | 345 | Load | 102,54 | 131,575 | 169,675 |
| *Bus2* | 345 | Load | 102 | 466,336 | 196,417 |
| *Bus3* | 345 | Load | 101,83 | 346,914 | 182,245 |
| *Bus4* | 345 | Load | 101,51 | 515,192 | 257,97 |
| *Bus5* | 345 | Load | 101,45 | 726,792 | 106,979 |
| *Bus6* | 345 | Load | 101,44 | 1054,595 | 208,8 |
| *Bus7* | 345 | Load | 101,42 | 327,601 | 94,876 |
| *Bus8* | 345 | Load | 101,45 | 577,277 | 313,125 |
| *Bus9* | 345 | Load | 102,38 | 39,813 | 311,332 |
| *Bus10* | 345 | Load | 101,58 | 649,518 | 135,895 |
| *Bus11* | 345 | Load | 101,52 | 293,725 | 136,422 |
| *Bus12* | 345 | Load | 100,22 | 7,533 | 88,383 |
| *Bus13* | 345 | Load | 101,57 | 355,718 | 69,996 |
| *Bus14* | 345 | Load | 101,61 | 352,113 | 144,103 |
| *Bus15* | 345 | Load | 101,85 | 331,936 | 298,789 |
| *Bus16* | 345 | Load | 102,1 | 866,774 | 460,853 |
| *Bus17* | 345 | Load | 101,99 | 212,34 | 130,908 |
| *Bus18* | 345 | Load | 101,91 | 176,513 | 103,714 |
| *Bus19* | 345 | Load | 102,64 | 628,702 | 297,756 |
| *Bus20* | 345 | Load | 98,22 | 605,85 | 204,208 |
| *Bus21* | 345 | Load | 102,12 | 601,481 | 123,233 |
| *Bus22* | 345 | Load | 102,3 | 649,575 | 146,402 |
| *Bus23* | 345 | Load | 102,42 | 605,708 | 294,784 |
| *Bus24* | 345 | Load | 102,18 | 345,881 | 158,937 |
| *Bus25* | 345 | Load | 102,06 | 538,231 | 93,121 |
| *Bus26* | 345 | Load | 102,03 | 400,985 | 61,497 |
| *Bus27* | 345 | Load | 101,94 | 292,021 | 78,461 |
| *Bus28* | 345 | Load | 102,15 | 345,464 | 44,429 |
| *Bus29* | 345 | Load | 102,24 | 824,469 | 91,274 |
| *Bus30* | 22 | Gen. | 100 | 250 | 31,095 |
| *Bus31* | 22 | SWING | 98,2 | 774,492 | 56,025 |
| *Bus32* | 22 | Gen. | 98,31 | 650 | 207,505 |
| *Bus33* | 22 | Gen. | 99,72 | 632 | 262,835 |
| *Bus34* | 22 | Gen. | 102 | 508 | 260,601 |
| *Bus35* | 22 | Gen. | 100 | 650 | 38,615 |
| *Bus36* | 22 | Gen. | 106,35 | 560 | 410,777 |
| *Bus37* | 22 | Gen. | 102,78 | 540 | 24,301 |
| *Bus38* | 22 | Gen. | 102,65 | 830 | 199,133 |
| *Bus39* | 345 | Gen. | 103 | 1171,234 | 729,781 |

### III.3.2 Study Case

#### III.3.2.1 Base Case – C0

In the base case (C0), all generators in the system are composed by synchronous machines with their associated controls. In this case, simulations for the separation scenario 1 and the separation scenario 2 are conducted to compare three different real UFLS schemes. Scheme 1, 2, and 3 are examples of (UFLS) schemes commonly used in power systems [43, 44]. Based on the results of these simulations, the optimal UFLS scheme will be selected and will be utilized in other cases. Table III.2 presents the settings for the various LS stages, providing a detailed overview of the parameters used in each stage. The flowchart depicted Figure III.10 provides a comprehensive overview of the selected UFLS schemes.

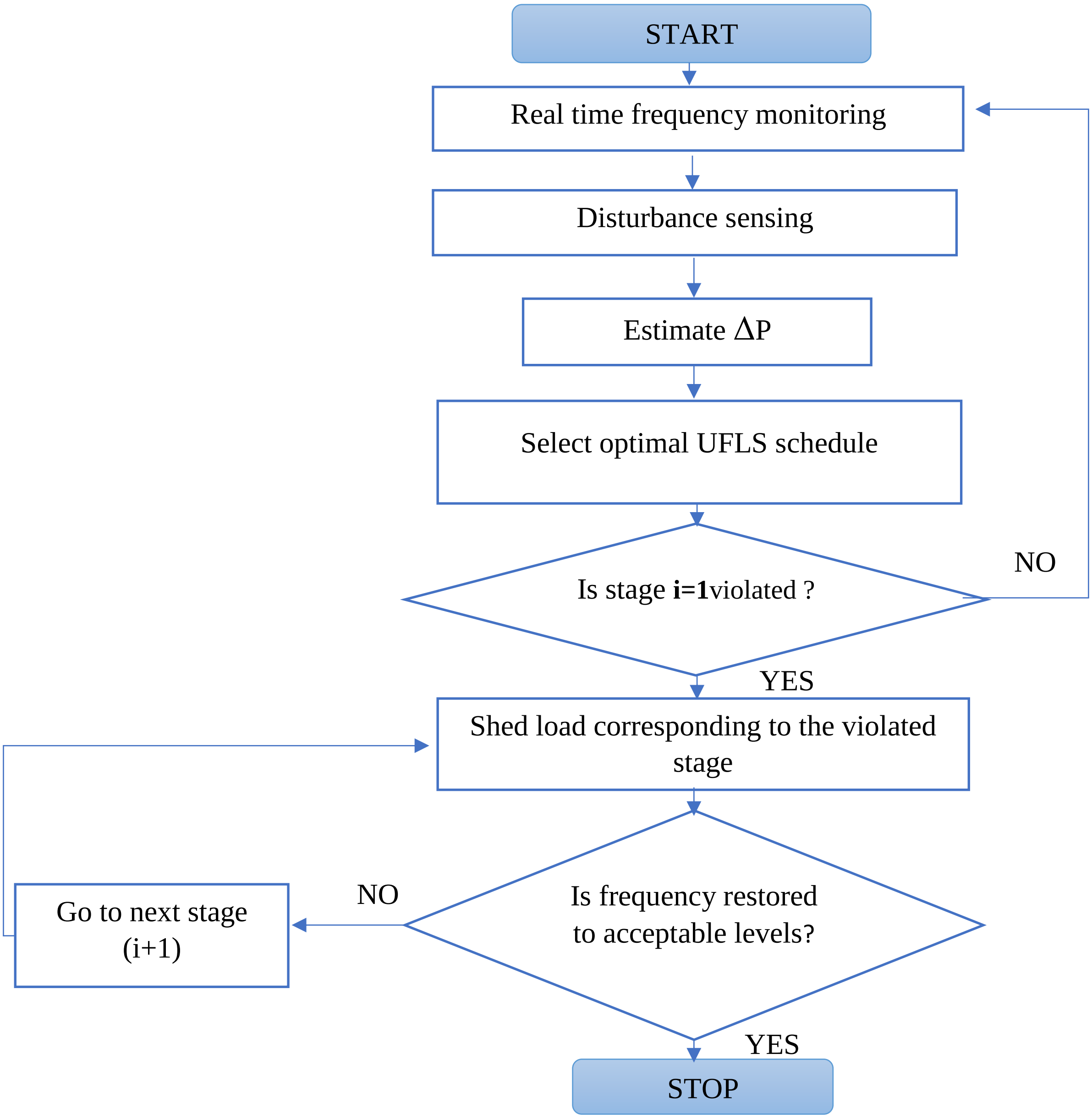


Figure III.10. Flowchart of the proposed UFLS control strategy

**Table III.2** Settings for the under frequency load shedding schemes

| | ***Frequency Threshold (Hz)*** | ***Shed Amount (%)*** | ***Delay(s)*** |
|---|---|---|---|
| ***Scheme*** *1* | *59,50* | *10%* | *00,20* |
| | *59,30* | *10%* | |
| | *58,80* | *10%* | |
| | *58,30* | *10%* | |
| ***Scheme*** *2* | *58.75* | *15%* | *00,10* |
| | *58.50* | *15%* | |
| | *58.00* | *15%* | |
| | *57.75* | *15%* | |
| ***Scheme*** *3* | *59,50* | *5%* | *00,10* |
| | *59,30* | *10%* | |
| | *58,80* | *15%* | |
| | *58,00* | *15%* | |

**III.3.2.1.1 Separation Scenario 1:** One transmission line tripped (N-1)

In the specific scenario being studied, a fault occurred at t = 0.1 s which caused the transmission line 16-19 to trip at t = 0.25 s, as depicted in Figure III.11. This disturbance led to an actual power deficit of -17.74% in the tested system. To simulate the under frequency load shedding (UFLS) condition, ETAP transient stability analysis was utilized. The study case conditions and frequency relay response for three schemes are depicted in Figure III.12, Figure III.13, and Figure III.14, respectively.

The simulation results for various UFLS schemes are presented in Figure III.15, Figure III.16, and Table III.3. The frequency response of buses 19, 20, 33, and 34, which were receiving power generation from generators 4 and 5 is presented in Figure III.17.

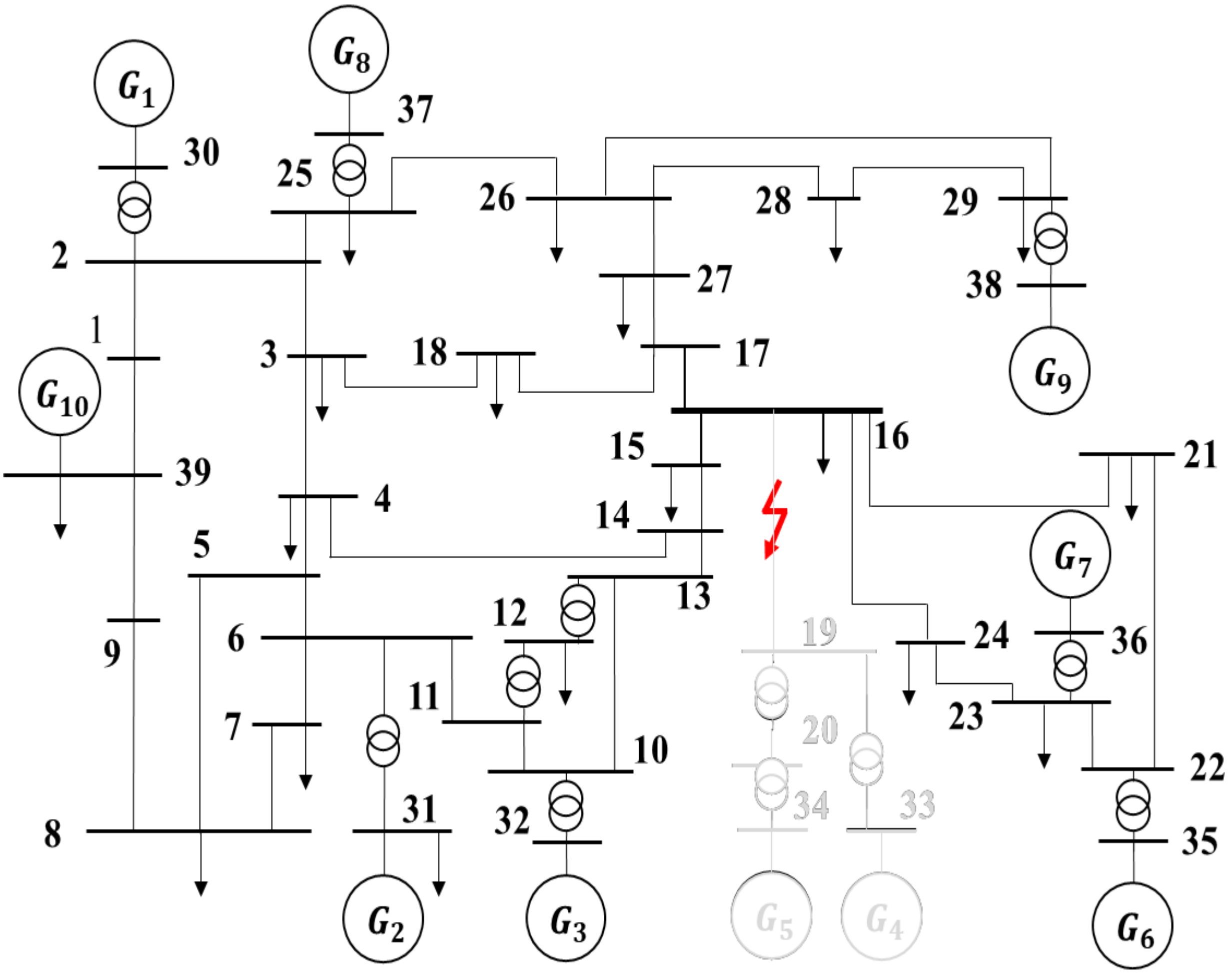
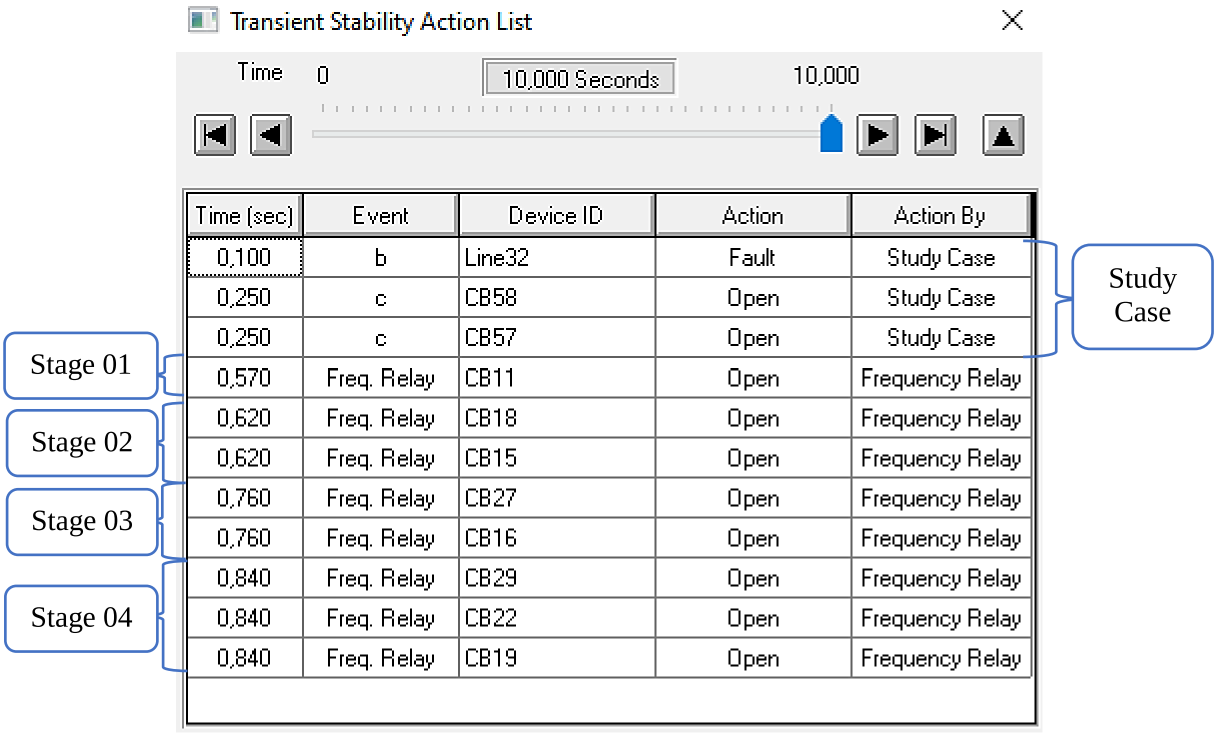
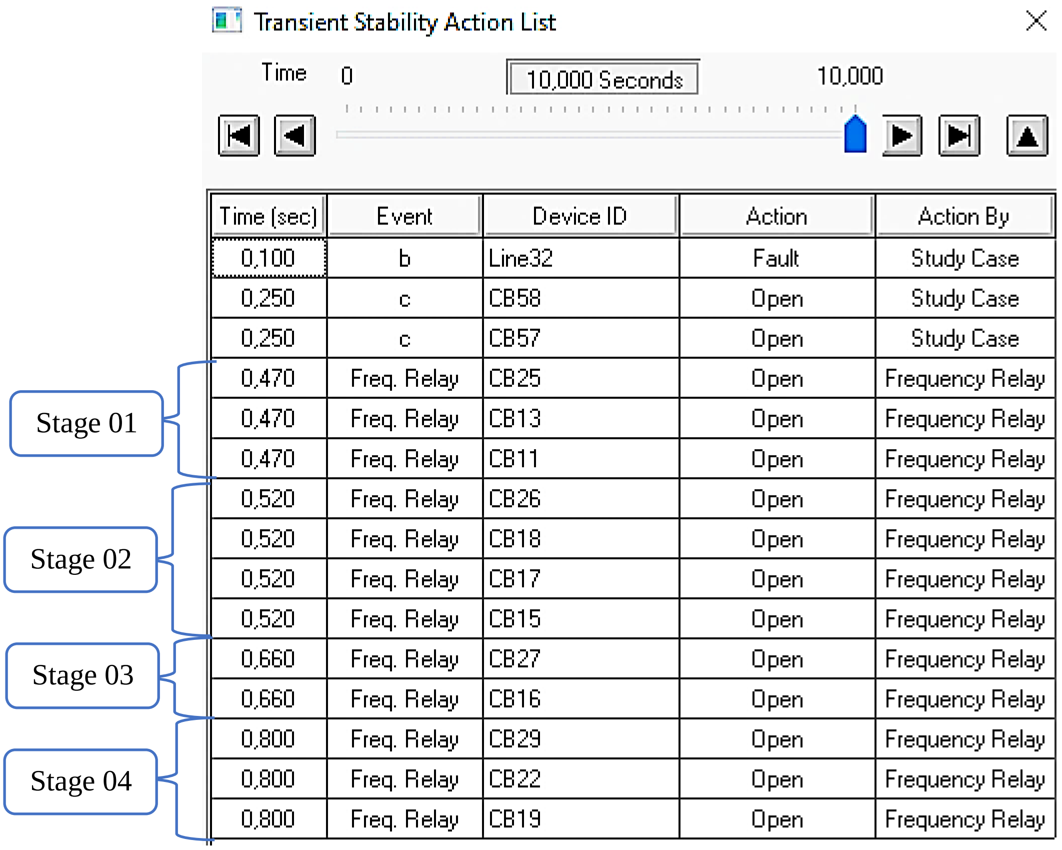


Figure III.11. Separation scenario 1 (One transmission line tripped)



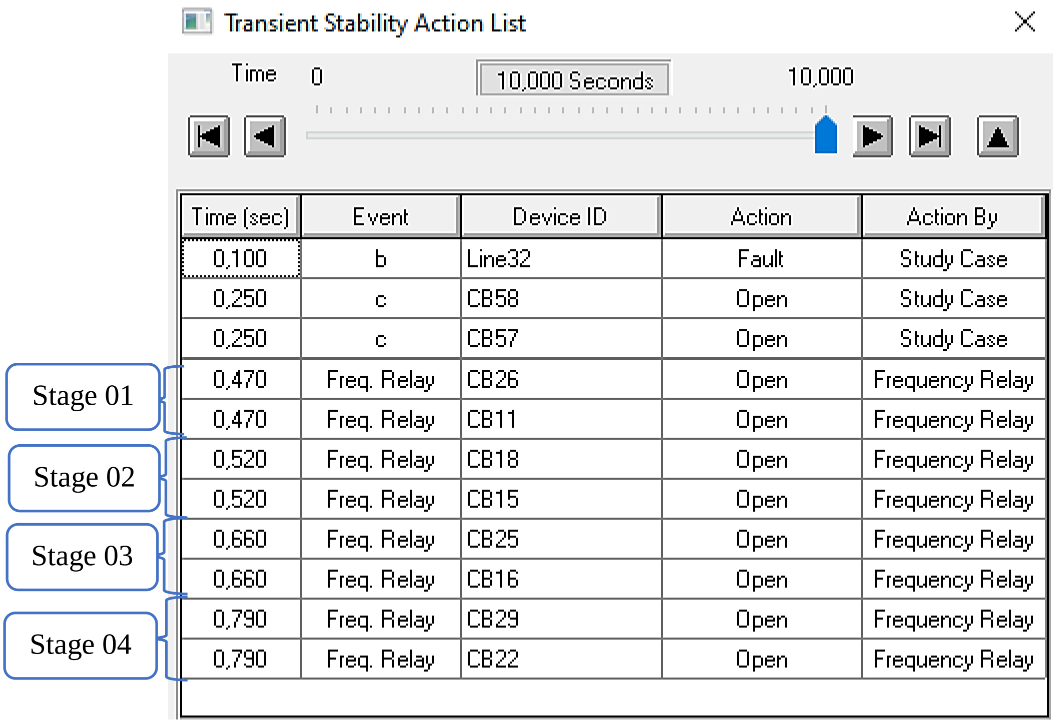
| Time (sec) | Event | Device ID | Action | Action By |
|---|---|---|---|---|
| 0,100 | b | Line32 | Fault | Study Case |
| 0,250 | c | CB58 | Open | Study Case |
| 0,250 | c | CB57 | Open | Study Case |
| 0,570 | Freq. Relay | CB11 | Open | Frequency Relay |
| 0,620 | Freq. Relay | CB18 | Open | Frequency Relay |
| 0,620 | Freq. Relay | CB15 | Open | Frequency Relay |
| 0,760 | Freq. Relay | CB27 | Open | Frequency Relay |
| 0,760 | Freq. Relay | CB16 | Open | Frequency Relay |
| 0,840 | Freq. Relay | CB29 | Open | Frequency Relay |
| 0,840 | Freq. Relay | CB22 | Open | Frequency Relay |
| 0,840 | Freq. Relay | CB19 | Open | Frequency Relay |

Figure III.12. Study case condition and frequency relay response in ETAP (scheme 1)



| Time (sec) | Event | Device ID | Action | Action By |
|---|---|---|---|---|
| 0,100 | b | Line32 | Fault | Study Case |
| 0,250 | c | CB58 | Open | Study Case |
| 0,250 | c | CB57 | Open | Study Case |
| 0,470 | Freq. Relay | CB25 | Open | Frequency Relay |
| 0,470 | Freq. Relay | CB13 | Open | Frequency Relay |
| 0,470 | Freq. Relay | CB11 | Open | Frequency Relay |
| 0,520 | Freq. Relay | CB26 | Open | Frequency Relay |
| 0,520 | Freq. Relay | CB18 | Open | Frequency Relay |
| 0,520 | Freq. Relay | CB17 | Open | Frequency Relay |
| 0,520 | Freq. Relay | CB15 | Open | Frequency Relay |
| 0,660 | Freq. Relay | CB27 | Open | Frequency Relay |
| 0,660 | Freq. Relay | CB16 | Open | Frequency Relay |
| 0,800 | Freq. Relay | CB29 | Open | Frequency Relay |
| 0,800 | Freq. Relay | CB22 | Open | Frequency Relay |
| 0,800 | Freq. Relay | CB19 | Open | Frequency Relay |

Figure III.13. Study case condition and frequency relay response in ETAP (scheme 2)



| Time (sec) | Event | Device ID | Action | Action By |
|---|---|---|---|---|
| 0,100 | b | Line32 | Fault | Study Case |
| 0,250 | c | CB58 | Open | Study Case |
| 0,250 | c | CB57 | Open | Study Case |
| 0,470 | Freq. Relay | CB26 | Open | Frequency Relay |
| 0,470 | Freq. Relay | CB11 | Open | Frequency Relay |
| 0,520 | Freq. Relay | CB18 | Open | Frequency Relay |
| 0,520 | Freq. Relay | CB15 | Open | Frequency Relay |
| 0,660 | Freq. Relay | CB25 | Open | Frequency Relay |
| 0,660 | Freq. Relay | CB16 | Open | Frequency Relay |
| 0,790 | Freq. Relay | CB29 | Open | Frequency Relay |
| 0,790 | Freq. Relay | CB22 | Open | Frequency Relay |

Figure III.14. Study case condition and frequency relay response in ETAP (scheme 3)

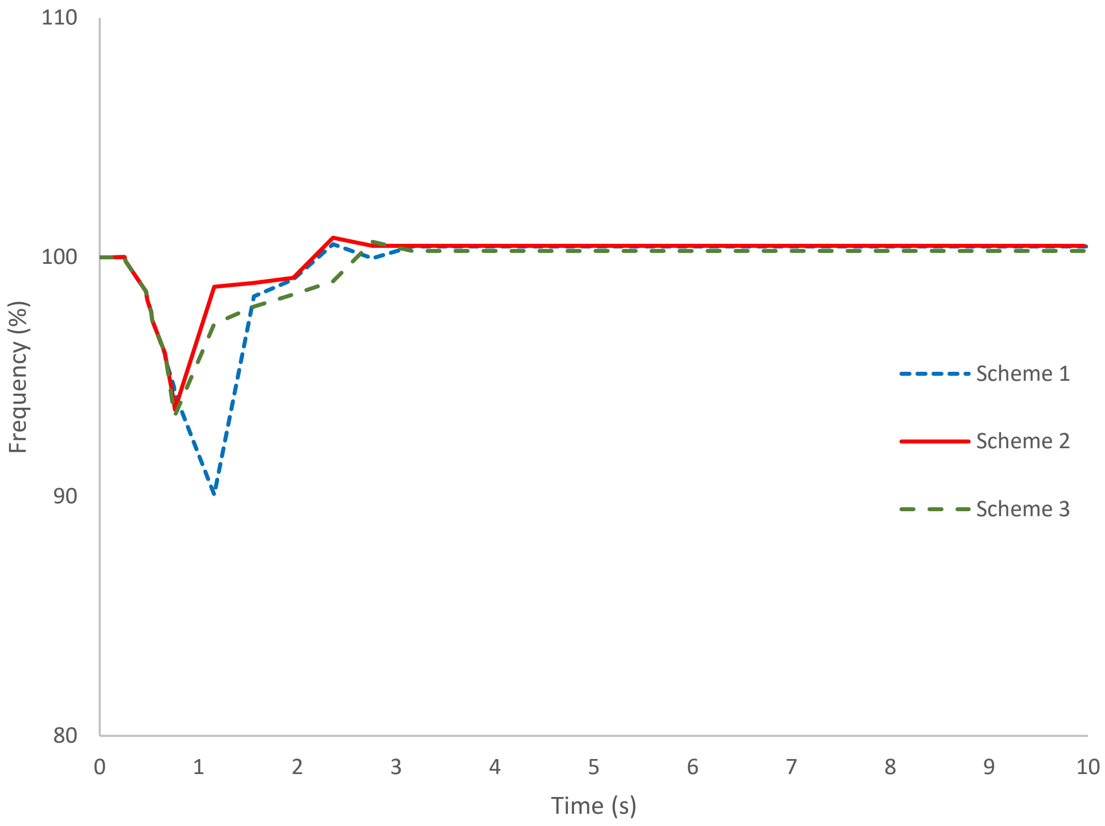


Figure III.15. Frequency curves under different UFLS schemes

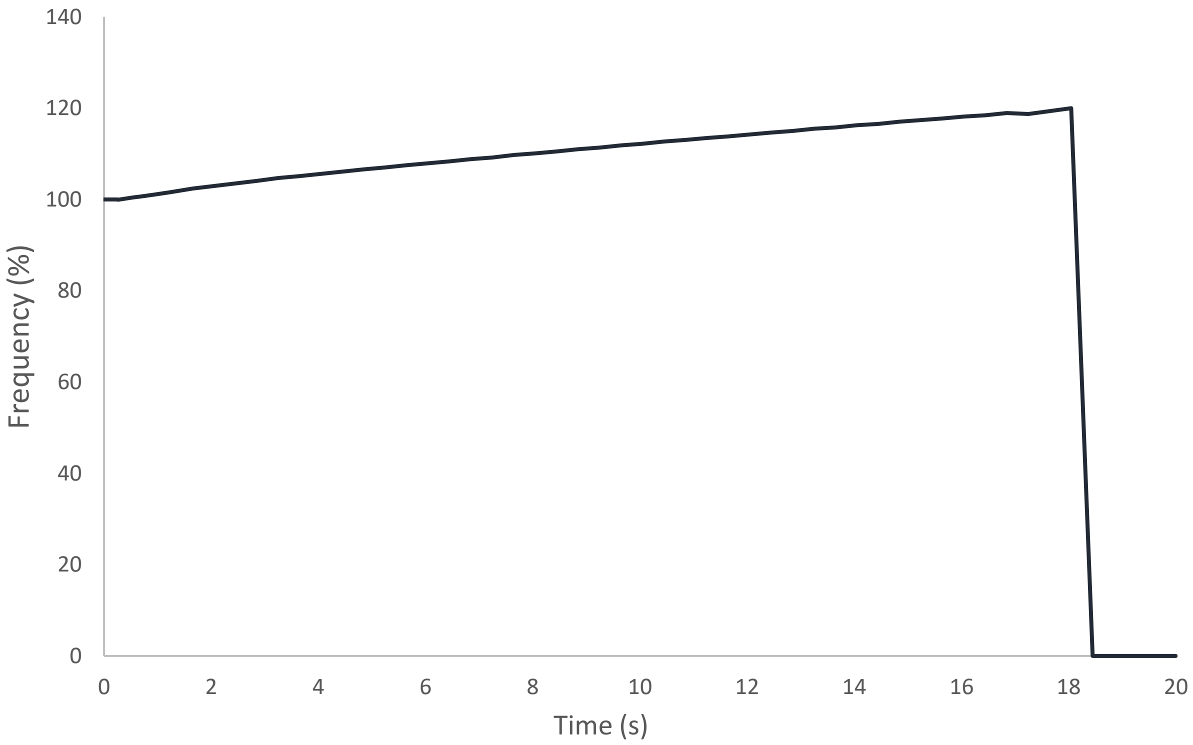


Figure III.16. The frequency response of buses 19, 20, 33, and 34

**Table III.3.** Load shedding amount of different UFLS schemes

| ***Load shedding stages*** | ***Load shedding amount (MW)*** | | |
|---|---|---|---|
| | ***Scheme 1*** | ***Scheme 2*** | ***Scheme 3*** |
| ***First stage*** | *642,53* | *963,79* | *321,26* |
| ***Second stage*** | *642,53* | *963,79* | *642,53* |
| ***Third stage*** | *642,53* | *963,79* | *963,79* |
| ***Fourth stage*** | *642,53* | *963,79* | *963,79* |
| ***Total*** | *2570,12* | *3855,16* | *2891,37* |

**Table III.4.** Undershoot frequency and time to frequency stability for UFLS schemes

| ***Scheme*** | ***Undershoot Frequency (Hz)*** | ***Time to Frequency Stability (seconds)*** |
|---|---|---|
| ***1*** | *5.96* | *2.91* |
| ***2*** | *3.89* | *2.51* |
| ***3*** | *3.98* | *2.91* |

The analysis of the simulation results presented in Figure III.15, Table III.3 and Table III.4 demonstrates that UFLS schemes 1, 2, and 3 are effective in restoring frequency stability after an under frequency event in the power system. Specifically, schemes 1 and 3 execute the UFLS process by undergoing four stages of load shedding, resulting in the restoration of frequency stability within 2.91 seconds. In contrast, scheme 2 achieves the same result in a shorter duration of 2.51 seconds, also requiring four stages of load shedding.

The frequency response characteristics observed in Figure III.16 for buses 19, 20, 33, and 34 are noteworthy. During the scenario, these buses were receiving electrical power supply from generators 4 and 5 and experienced an over frequency event, followed by a blackout. The generators' protection system activated at t=18.05 s after the separation event, which led to the blackout.

In conclusion, the results obtained indicate that scheme 2 and scheme 3 demonstrate a higher level of effectiveness in restoring frequency stability compared to scheme 1. Additionally, the load amount in scheme 3 is smaller than that in scheme 2. However, it is important to acknowledge that further analysis may be necessary to validate this conclusion and ensure its robustness.

### III.3.2.1.2 Separation Scenario 2: Four transmission line tripped (N-4)

In this analyzed scenario, a fault was recorded at t=0.1s, which led to the tripping of four transmission lines. The specific lines that were disconnected include line 09-39, line 02-03, line 03-18, and line 14-15. The purpose behind selectively tripping these transmission lines was to intentionally induce a more severe separation between different sections of the tested system. This deliberate disconnection aimed to create challenging conditions for the power system, allowing for a comprehensive evaluation of its response and performance under highly stressed and separated operating states.

However, as a consequence of the disturbance, the tested system experienced a significant event at t=0.25s, resulting in the system splitting into two distinct islands, as depicted in Figure III.17. Island 1 encountered an actual power deficit of -6.77%, indicating that the power demand on this particular island surpassed its available generation capacity. This disparity between demand and generation capacity signifies the strain and imbalance in meeting the electricity needs of island 1, posing challenges for maintaining a stable and reliable power supply in that region.

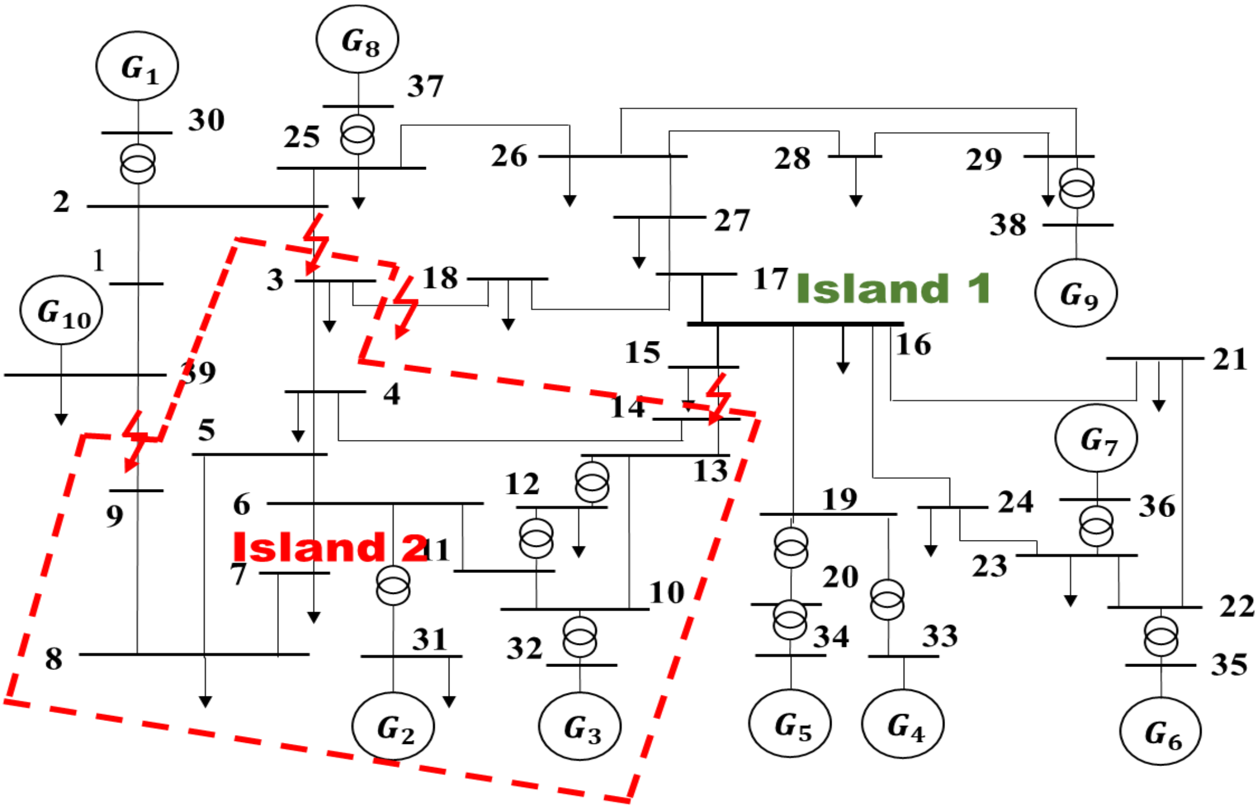
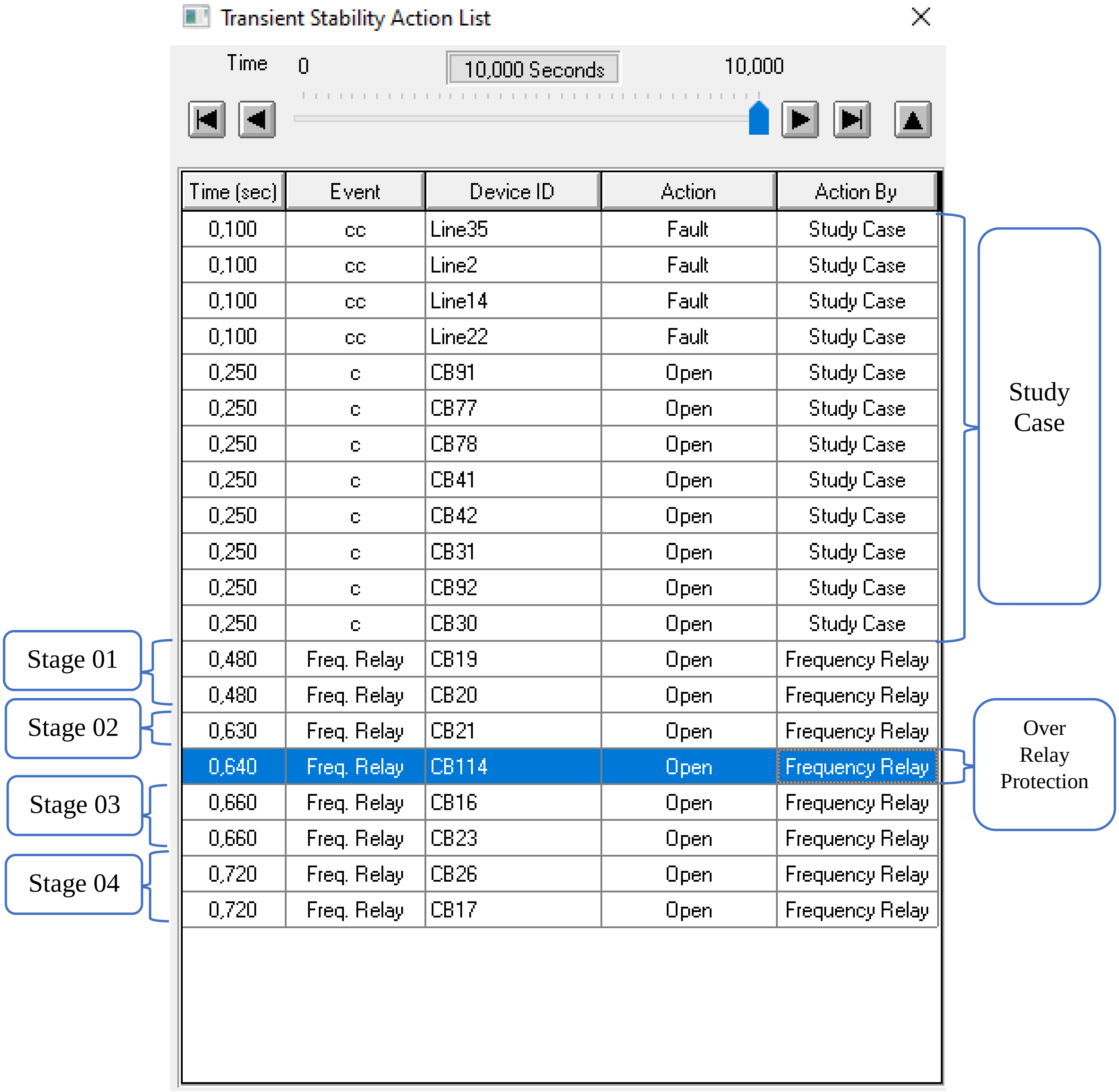


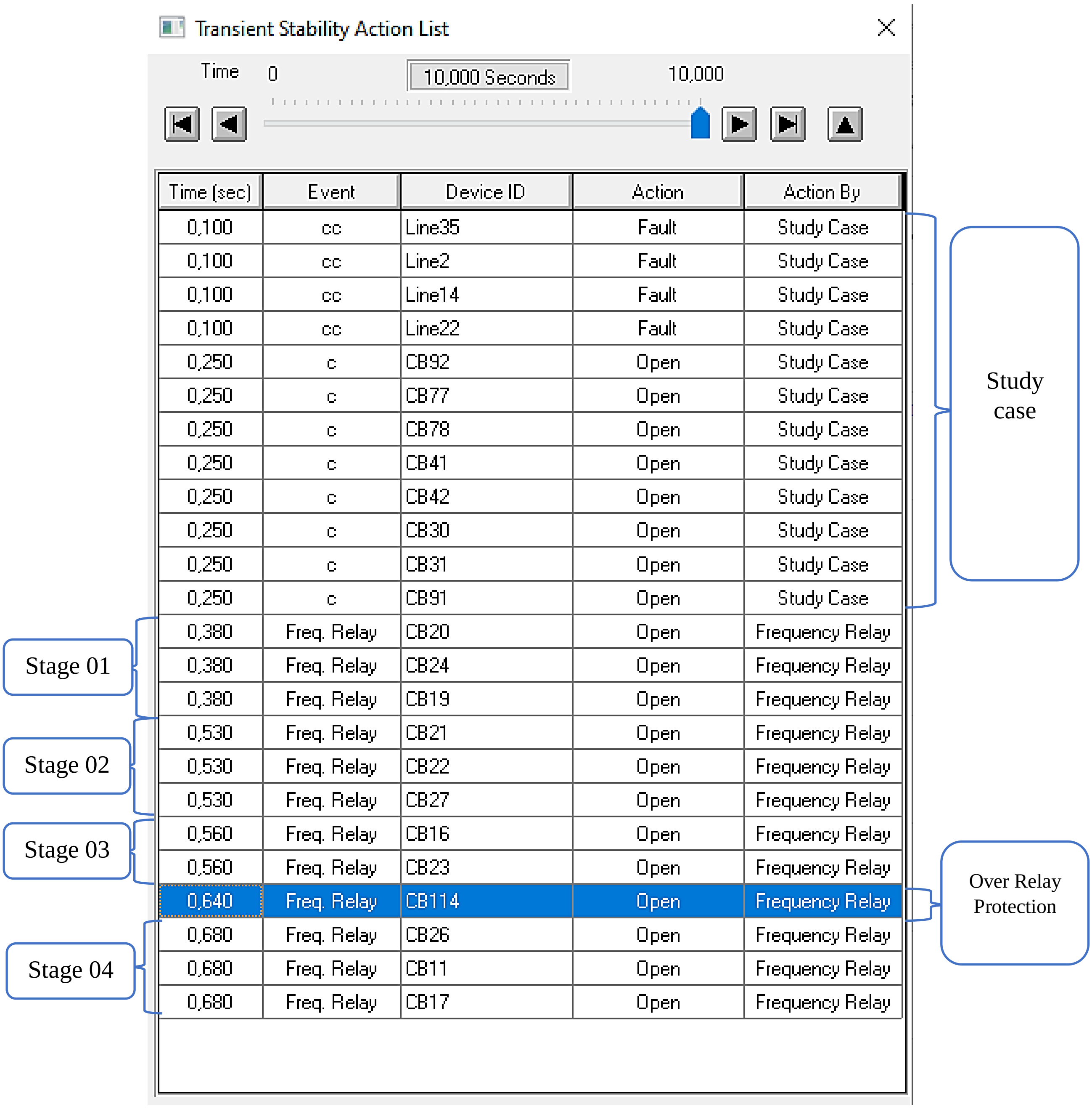
Figure III.17. Separation scenario 2 (Four transmission line tripped)

The study case conditions and the corresponding frequency relay responses for three schemes are visually represented in Figure III.18, Figure III.19, and Figure III.20, respectively. These figures provide a comprehensive overview of the system conditions and the behavior of the frequency relays under the three different schemes.



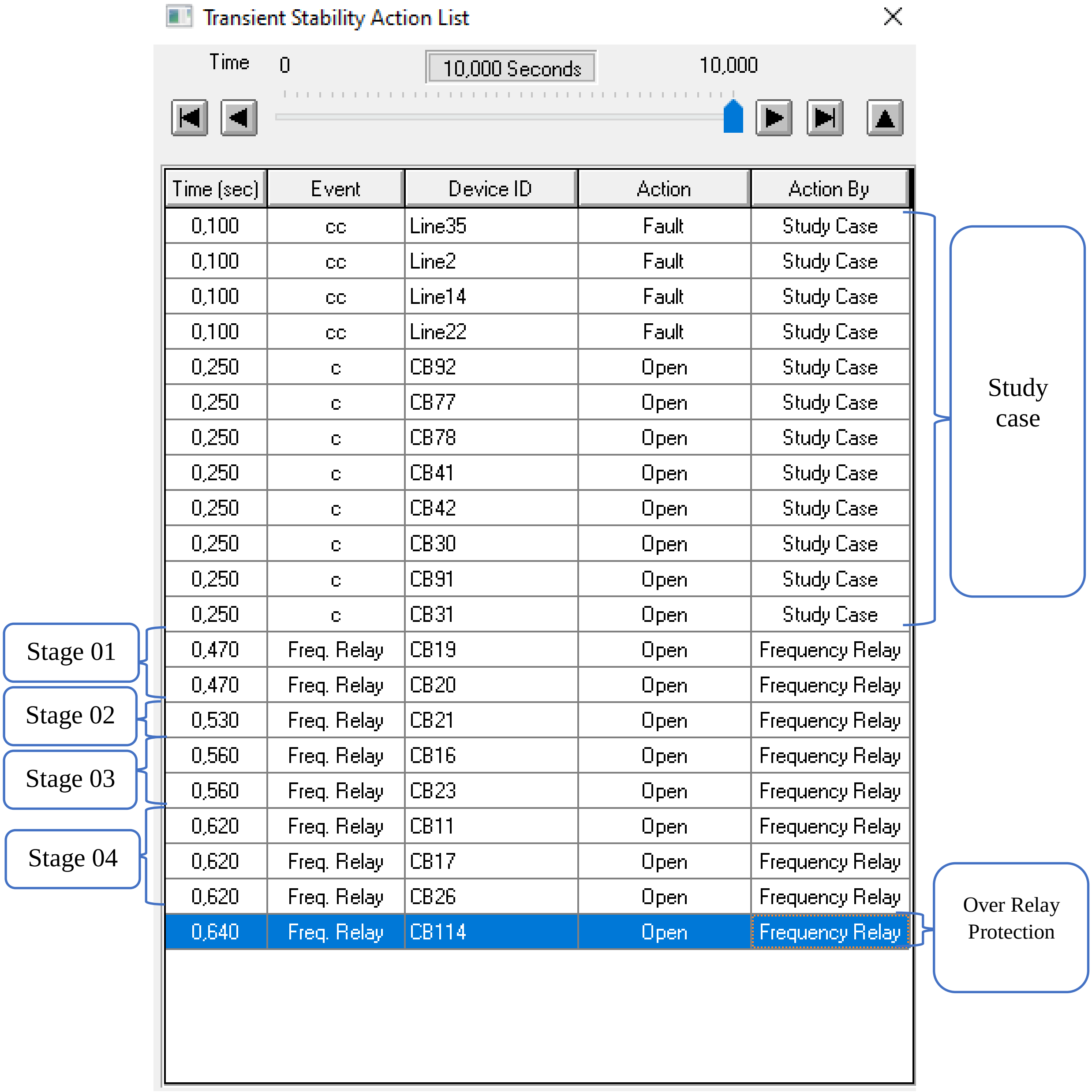
| Time (sec) | Event | Device ID | Action | Action By |
|---|---|---|---|---|
| 0,100 | cc | Line35 | Fault | Study Case |
| 0,100 | cc | Line2 | Fault | Study Case |
| 0,100 | cc | Line14 | Fault | Study Case |
| 0,100 | cc | Line22 | Fault | Study Case |
| 0,250 | c | CB91 | Open | Study Case |
| 0,250 | c | CB77 | Open | Study Case |
| 0,250 | c | CB78 | Open | Study Case |
| 0,250 | c | CB41 | Open | Study Case |
| 0,250 | c | CB42 | Open | Study Case |
| 0,250 | c | CB31 | Open | Study Case |
| 0,250 | c | CB92 | Open | Study Case |
| 0,250 | c | CB30 | Open | Study Case |
| 0,480 | Freq. Relay | CB19 | Open | Frequency Relay |
| 0,480 | Freq. Relay | CB20 | Open | Frequency Relay |
| 0,630 | Freq. Relay | CB21 | Open | Frequency Relay |
| 0,640 | Freq. Relay | CB114 | Open | Frequency Relay |
| 0,660 | Freq. Relay | CB16 | Open | Frequency Relay |
| 0,660 | Freq. Relay | CB23 | Open | Frequency Relay |
| 0,720 | Freq. Relay | CB26 | Open | Frequency Relay |
| 0,720 | Freq. Relay | CB17 | Open | Frequency Relay |

Figure III.18. Study case condition and frequency relay response in ETAP (scheme 1)



| Time (sec) | Event | Device ID | Action | Action By |
|---|---|---|---|---|
| 0,100 | cc | Line35 | Fault | Study Case |
| 0,100 | cc | Line2 | Fault | Study Case |
| 0,100 | cc | Line14 | Fault | Study Case |
| 0,100 | cc | Line22 | Fault | Study Case |
| 0,250 | c | CB92 | Open | Study Case |
| 0,250 | c | CB77 | Open | Study Case |
| 0,250 | c | CB78 | Open | Study Case |
| 0,250 | c | CB41 | Open | Study Case |
| 0,250 | c | CB42 | Open | Study Case |
| 0,250 | c | CB30 | Open | Study Case |
| 0,250 | c | CB31 | Open | Study Case |
| 0,250 | c | CB91 | Open | Study Case |
| 0,380 | Freq. Relay | CB20 | Open | Frequency Relay |
| 0,380 | Freq. Relay | CB24 | Open | Frequency Relay |
| 0,380 | Freq. Relay | CB19 | Open | Frequency Relay |
| 0,530 | Freq. Relay | CB21 | Open | Frequency Relay |
| 0,530 | Freq. Relay | CB22 | Open | Frequency Relay |
| 0,530 | Freq. Relay | CB27 | Open | Frequency Relay |
| 0,560 | Freq. Relay | CB16 | Open | Frequency Relay |
| 0,560 | Freq. Relay | CB23 | Open | Frequency Relay |
| 0,640 | Freq. Relay | CB114 | Open | Frequency Relay |
| 0,680 | Freq. Relay | CB26 | Open | Frequency Relay |
| 0,680 | Freq. Relay | CB11 | Open | Frequency Relay |
| 0,680 | Freq. Relay | CB17 | Open | Frequency Relay |

Figure III.19. Study case condition and frequency relay response in ETAP (scheme 2)



| Time (sec) | Event | Device ID | Action | Action By |
|---|---|---|---|---|
| 0,100 | cc | Line35 | Fault | Study Case |
| 0,100 | cc | Line2 | Fault | Study Case |
| 0,100 | cc | Line14 | Fault | Study Case |
| 0,100 | cc | Line22 | Fault | Study Case |
| 0,250 | c | CB92 | Open | Study Case |
| 0,250 | c | CB77 | Open | Study Case |
| 0,250 | c | CB78 | Open | Study Case |
| 0,250 | c | CB41 | Open | Study Case |
| 0,250 | c | CB42 | Open | Study Case |
| 0,250 | c | CB30 | Open | Study Case |
| 0,250 | c | CB91 | Open | Study Case |
| 0,250 | c | CB31 | Open | Study Case |
| 0,470 | Freq. Relay | CB19 | Open | Frequency Relay |
| 0,470 | Freq. Relay | CB20 | Open | Frequency Relay |
| 0,530 | Freq. Relay | CB21 | Open | Frequency Relay |
| 0,560 | Freq. Relay | CB16 | Open | Frequency Relay |
| 0,560 | Freq. Relay | CB23 | Open | Frequency Relay |
| 0,620 | Freq. Relay | CB11 | Open | Frequency Relay |
| 0,620 | Freq. Relay | CB17 | Open | Frequency Relay |
| 0,620 | Freq. Relay | CB26 | Open | Frequency Relay |
| 0,640 | Freq. Relay | CB114 | Open | Frequency Relay |

Figure III.20. Study case condition and frequency relay response in ETAP (scheme 3)

The simulation results for the frequency response of both island 1 and island 2, considering the implementation of under frequency load shedding and over relay protection, under three different schemes, are displayed in Figure III.21 and Figure III.22, respectively. These figures offer a clear visual representation of the dynamic behavior of the frequency in each island, showcasing the impact and effectiveness of the implemented measures across the different schemes.

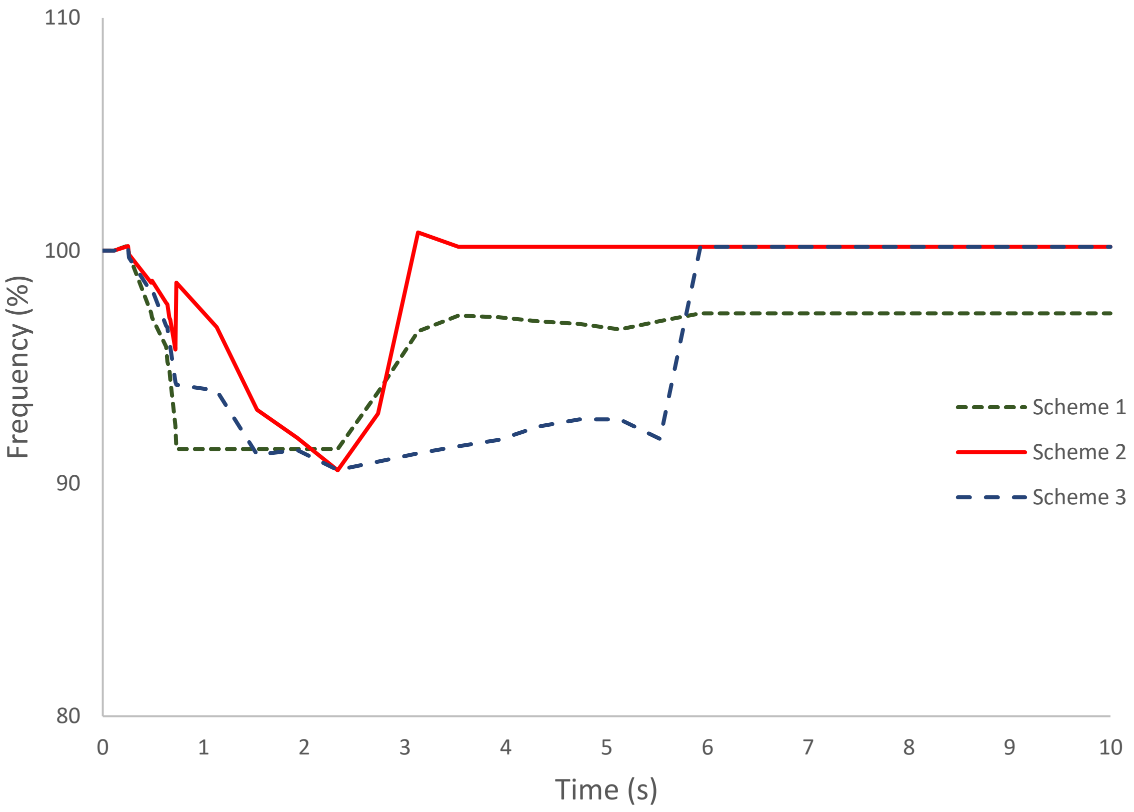


Figure III.21. Frequency curves for the island 1 under different UFLS schemes

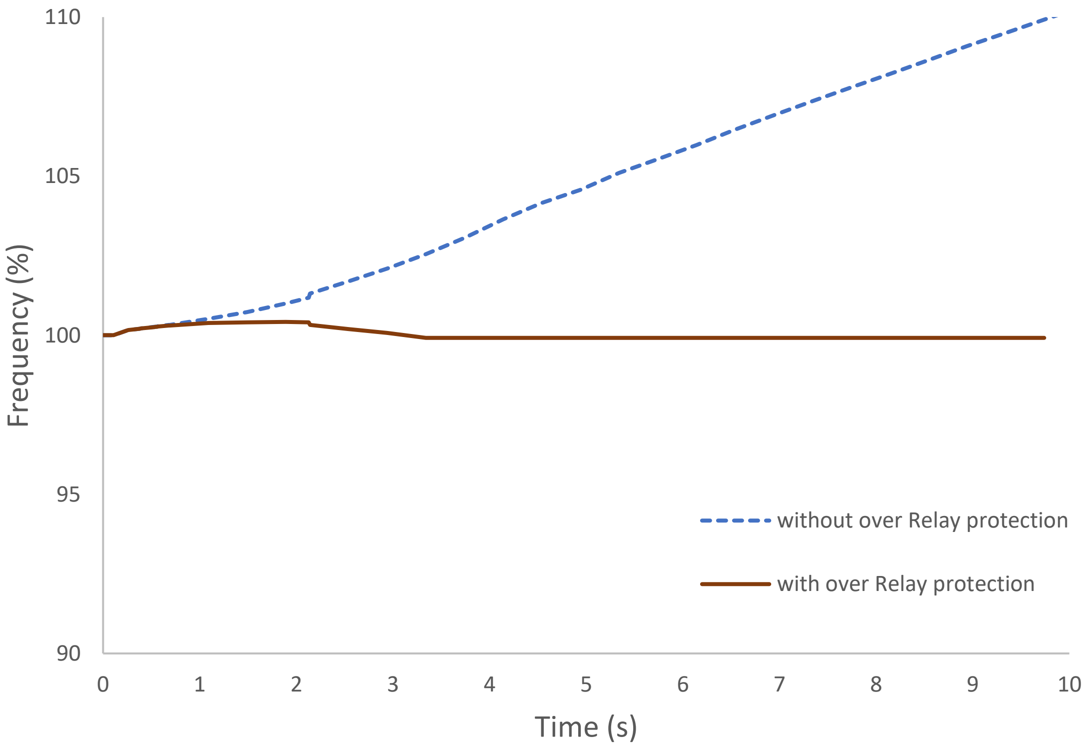


Figure III.22. Frequency curves for the island 2

**Table III.5.** Load shedding amount of different UFLS schemes

| ***Load shedding stages*** | ***Load shedding amount (MW)*** | | |
|---|---|---|---|
| | ***Scheme 1*** | ***Scheme 2*** | ***Scheme 3*** |
| ***First stage*** | *472.83* | *709.24* | *236.42* |
| ***Second stage*** | *472.83* | *709.24* | *472.83* |
| ***Third stage*** | *472.83* | *709.24* | *709.24* |
| ***Fourth stage*** | *472.83* | *709.24* | *709.24* |
| ***Total*** | *1891.32* | *2836.96* | *2127.73* |

**Table III.6.** Undershoot frequency and time to frequency stability for UFLS schemes

| ***Scheme*** | ***Undershoot Frequency (Hz)*** | ***Time to Frequency Stability (seconds)*** |
|---|---|---|
| ***1*** | *5.12* | *Not achieved* |
| ***2*** | *5.65* | *3.24* |
| ***3*** | *5.67* | *5.68* |

Figure III.21 and Figure III.22 show the behavior of the frequency after applying under/over frequency load shedding in each island following the fault that caused the power imbalance between island 1 and island 2.

It can be observed that at t = 0.25 s, when the interconnection is lost, island 1 experiences under frequency conditions. In this scenario, the performance of the Under Frequency Load Shedding (UFLS) schemes becomes evident. While scheme 1 fails to restore frequency stability, as it is unable to prevent the frequency from crossing the collapse limit, scheme 2 and scheme 3 prove successful in ensuring frequency stability restoration. Scheme 2 accomplishes this task by implementing four stages of load shedding within a duration of 3.24 seconds, while scheme 3 achieves the restoration of frequency stability in 5.68 seconds.

On the other hand, island 2 faced over frequency conditions due to the interconnection loss, which were prevented by shedding 150 MW of power generation through over frequency protection.

Based on the findings from the two scenarios, it is evident that both scheme 2 and scheme 3 demonstrate effectiveness in restoring frequency stability. However, it is noteworthy that the load amount in scheme 3 is smaller than that in scheme 2. Despite this, scheme 2 demonstrates superior results in terms of frequency stability restoration. Therefore, based on these results, it is recommended to prioritize the implementation of scheme 2 in future scenarios to ensure efficient restoration of frequency stability. By adopting scheme 2, it is expected that the tested system will maintain its stability and reliability at a higher level. Furthermore, the results obtained from case C0, where all generators are synchronous machines, indicate the system's capability to restore frequency stability in different scenarios by implementing the selected load shedding scheme. The successful mitigation of under frequency conditions in scenario 1 and scenario 2 highlights the effectiveness of the scheme 2 in preserving system stability following interconnection loss.

### III.3.2.2 Case with RES – C1

For the purpose of studying the impact of Renewable Energy Sources (RES) penetration, case with RES (C1) has been designed. In this case, 30% of the power system's generation, which is currently provided by synchronous units (G7, G8, and G9), will be replaced with RES generation. This study aims to assess the effects of this change by subjecting the system to various scenarios, similar to those used in the base case (C0), where disturbances were introduced. The single-line diagram simulation for this study case is presented in Appendix C.

To provide an overview of the impact of these RES on the system, Table III.7 summarizes the key findings and observations resulting from the integration of renewable energy sources.

**Table III.7.** Impact of replacement synchronous generators by RES

| ***Case*** | $H_{sys}$ **(s)** |
|---|---|
| ***Base case – C0*** | *98,13* |
| ***Case with RES – C1*** | *80,24* |

#### III.3.2.2.1 Separation Scenario 1: One transmission line tripped

The same scenario as presented in the previous figure (Figure III.11) was used as disturbances in the tested system to analyze the effect of Renewable Energy Sources (RES) on frequency stability. Figure III.23 and Table III.8 shows the simulation results.

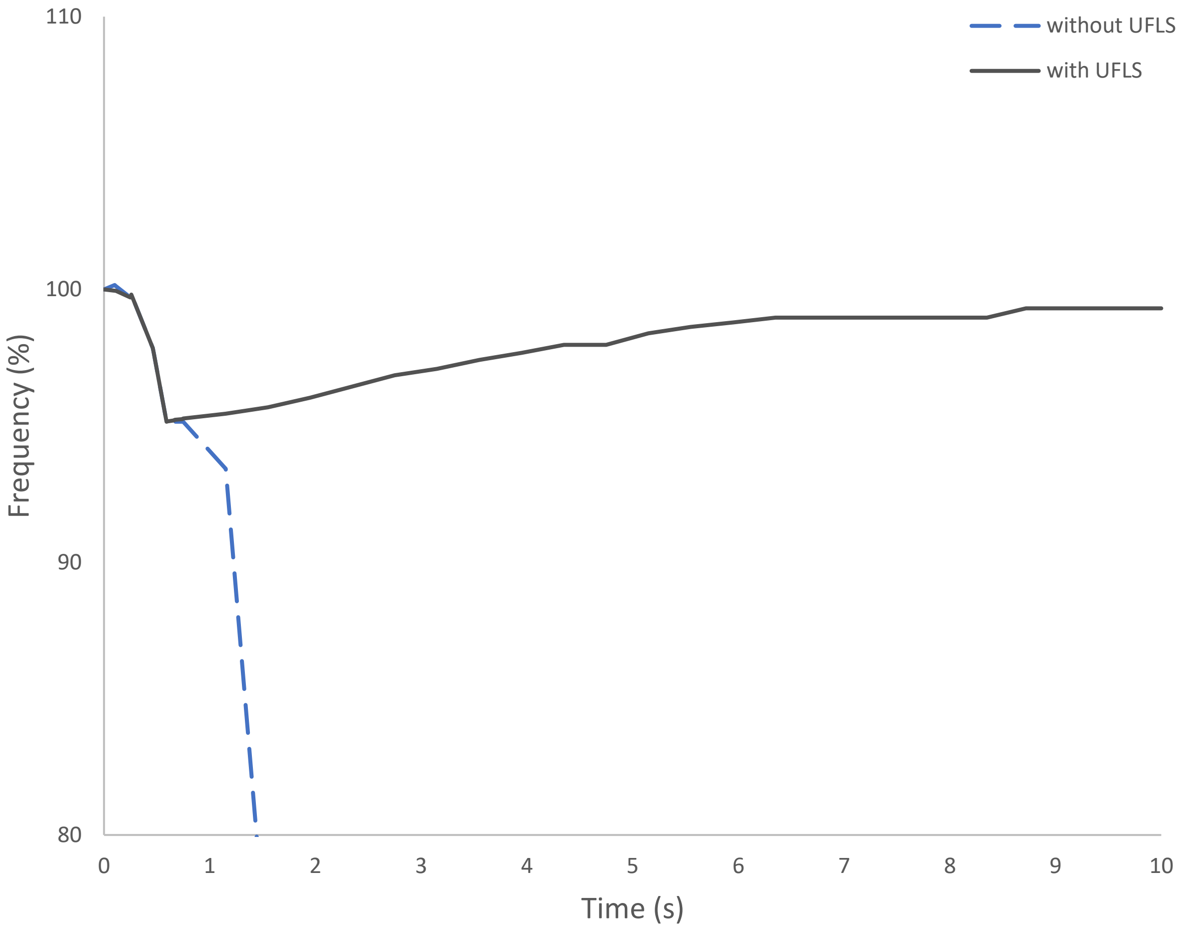


Figure III.23. Frequency behavior in the analyzed separation scenario 1 (scheme 2)

Table III.7 presents compelling evidence highlighting the impact of integrating Renewable Energy Sources (RES) into the power system. The data reveals a substantial reduction of 22.43% in the system's inertia as a consequence of RES integration. This reduction in inertia is a direct outcome of incorporating non-synchronous generators, such as RES, into the grid.

The analysis of Figure III.23 provides clear insights into the performance of the UFLS schemes. Scheme effectively demonstrates its capability in executing the Under Frequency Load Shedding (UFLS) process by implementing four stages of load shedding. This deliberate action results in the restoration of frequency stability, albeit over a longer duration of 8.48

seconds. In comparison, in the base case scenario, the scheme proved to be more efficient as it successfully restored frequency stability in a shorter duration of 2.51 seconds. By employing the same four stages of load shedding, the scheme effectively managed the frequency deviation and brought it back within an acceptable range.

**III.3.2.2.2 Separation Scenario 2:** Four transmission line tripped

In a comparable setting to that illustrated in the previous figure (Figure III.17), similar interconnection losses were simulated with a 30% penetration of Renewable Energy Sources (RES) in each of the islands.

The outcomes of these simulations for the island 1 and the island 2 are depicted in Figures III.24 and Figures III.25, respectively.

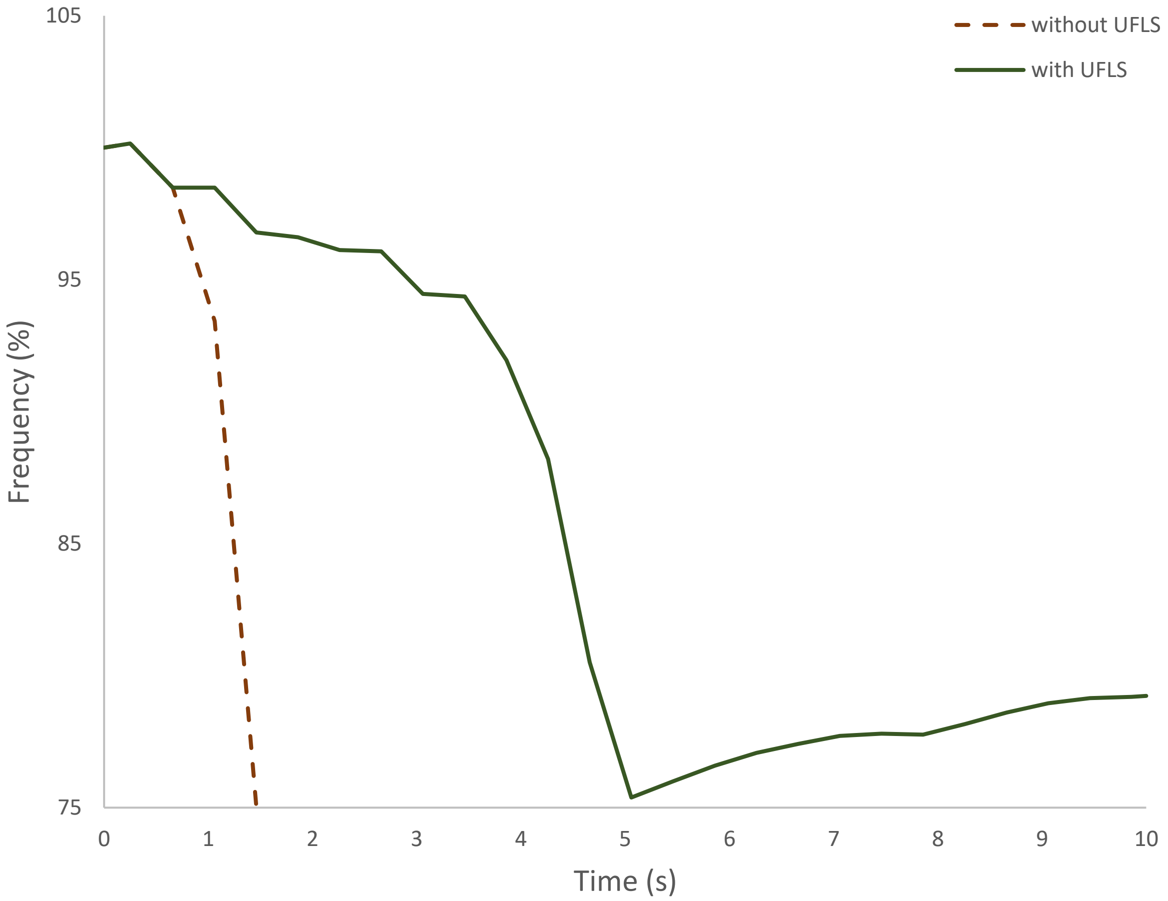


Figure III.24. Frequency curves for the island 1 (scheme 2)

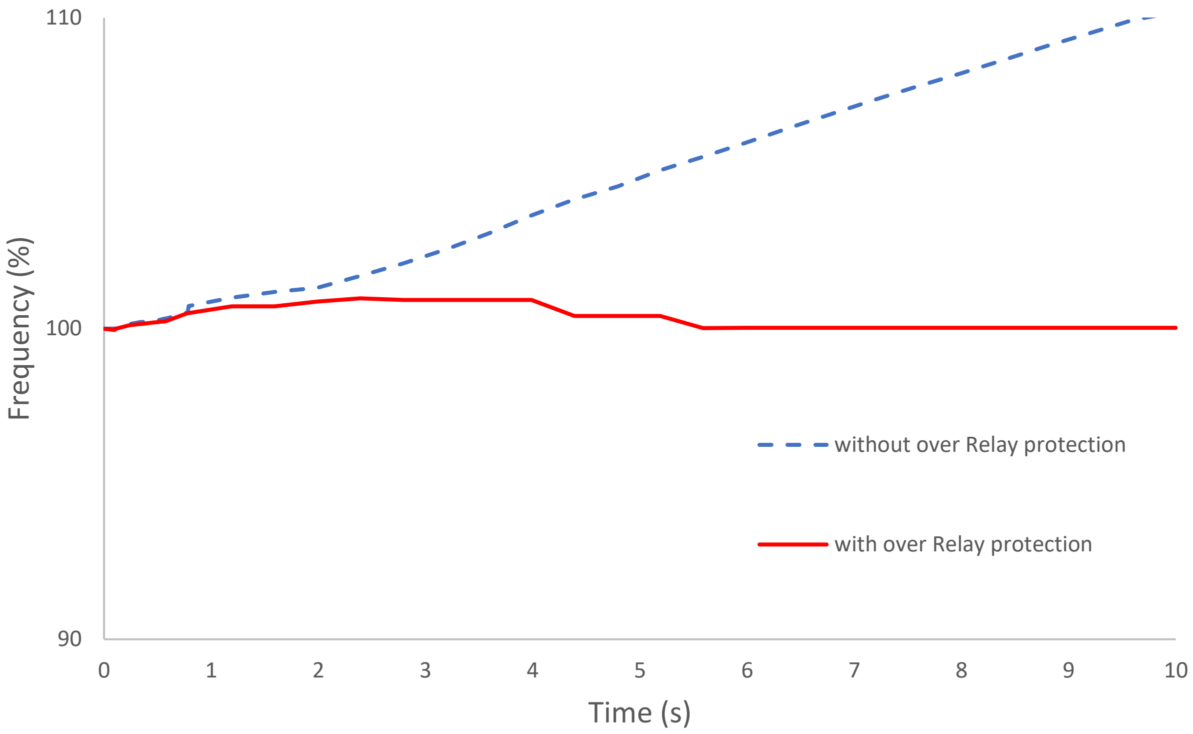


Figure III.25. Frequency curves for the island 2

**Table III.8.** Undershoot frequency and time to frequency stability

| *Scenario* | *Undershoot Frequency (Hz)* | *Time to Frequency Stability (seconds)* |
|---|---|---|
| ***Scenario 1*** | *2.91* | *8.48* |
| ***Scenario 2 (Island 1)*** | *14.71* | *Not achieved* |

It can be observed from Figure III.24 that at t = 0.25 s, when the interconnection was lost and the inertia was reduced, island 1 experienced under frequency conditions. The UFLS scheme was activated and underwent four stages of load shedding. However, despite these measures, the system was unable to return to an acceptable operating point. In contrast, based on the analysis of Figure III.25. Island 2 faced the same over frequency conditions due to the interconnection loss as the base case study, which were prevented over frequency relay protection.

Upon introducing a high penetration of Renewable Energy Sources (RES), as in case C1 with 30% penetration of RES, the results indicate that the power system is not capable of recovering frequency stability in various scenarios through the proposed load shedding scheme. This finding suggests that the integration of non-synchronous generators, such as RES, can significantly impact the frequency stability of the power system, requiring the development of new mitigation strategies. One of the key reasons behind this impact is the low inertia characteristic of non-synchronous generators after their integration. In traditional power systems, synchronous generators contribute to system inertia, which plays a crucial role in maintaining frequency stability. However, the introduction of non-synchronous generators like RES reduces the overall system inertia, making it more challenging to restore and maintain stable frequency levels. As a result, there is a need to propose an alternative scheme that can effectively address the challenges associated with high penetration of RES and ensure frequency stability in the power system.

#### III.3.2.3 Case with RES and a Newly Proposed Scheme

In this case, after extensive experiences and observations regarding the impact of increasing the load in each stage, a new scheme has been proposed. This proposed scheme aims to effectively tackle the challenges related to the integration of Renewable Energy Sources (RES) while ensuring frequency stability in the power system. The insights gained from practical implementation and analysis have contributed to the development of this scheme, which offers enhanced solutions to address the unique characteristics and requirements of RES integration. The newly proposed scheme consists of four stages, each with a specific shedding amount and the same delay. In total, 60% of the load will be shed across these stages, with the largest shedding amount occurring in the first stage at 35%. This progressive shedding approach allows for a controlled reduction of load in a step-by-step manner, ensuring a smoother transition and minimizing the sudden impact on the power system. By implementing this scheme, it is expected that the frequency stability of the system can be effectively restored. Table III.9 presents the settings of the newly proposed scheme.

**Table III.9.** Settings of the proposed load shedding stages

| *Frequency Threshold (Hz)* | *Shed Amount (%)* | *Delay(s)* |
|---|---|---|
| *59,80* | *35%* | *00,10* |
| *59,40* | *15%* | |
| *59,20* | *5%* | |
| *58,80* | *5%* | |

The simulation results for the two scenarios with the newly proposed scheme are illustrated in Figure III.26 and Figure III.27, respectively. These figures provide a visual representation of the system's behavior and response under the influence of the new proposed scheme.

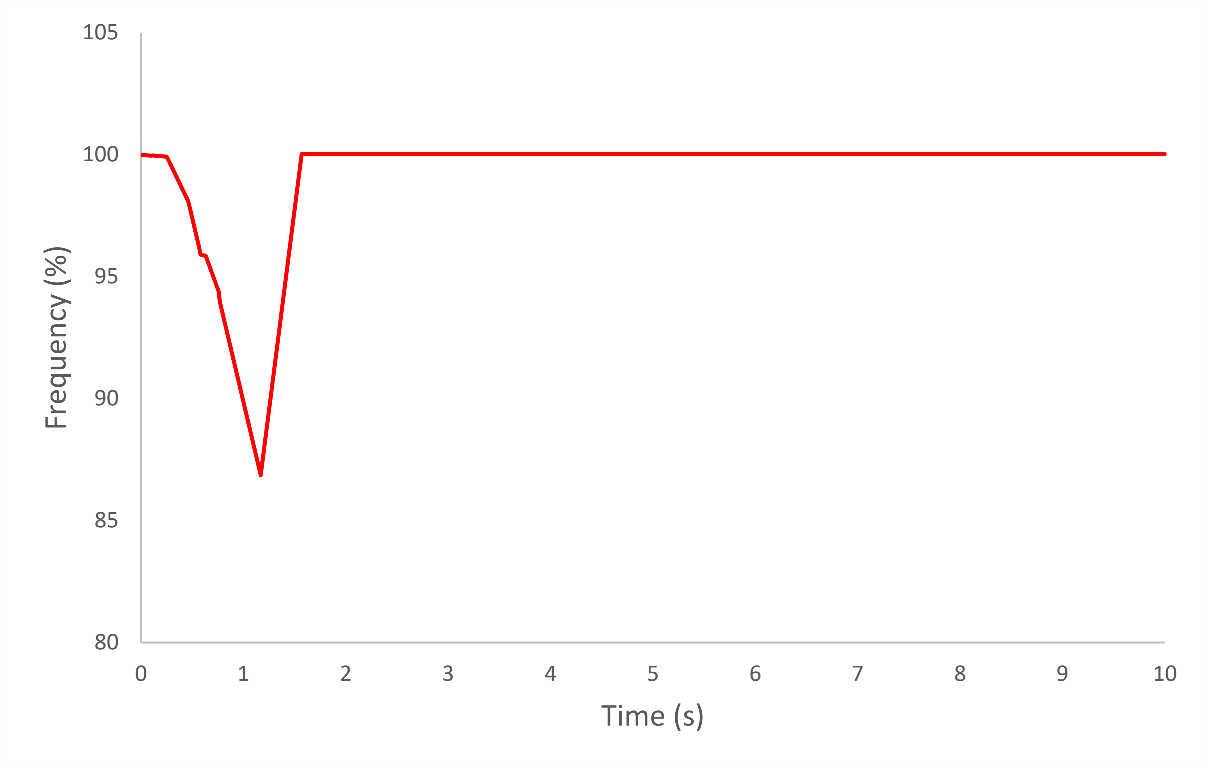


Figure III.26. Frequency behavior in the analyzed separation scenario 1 with the newly proposed scheme

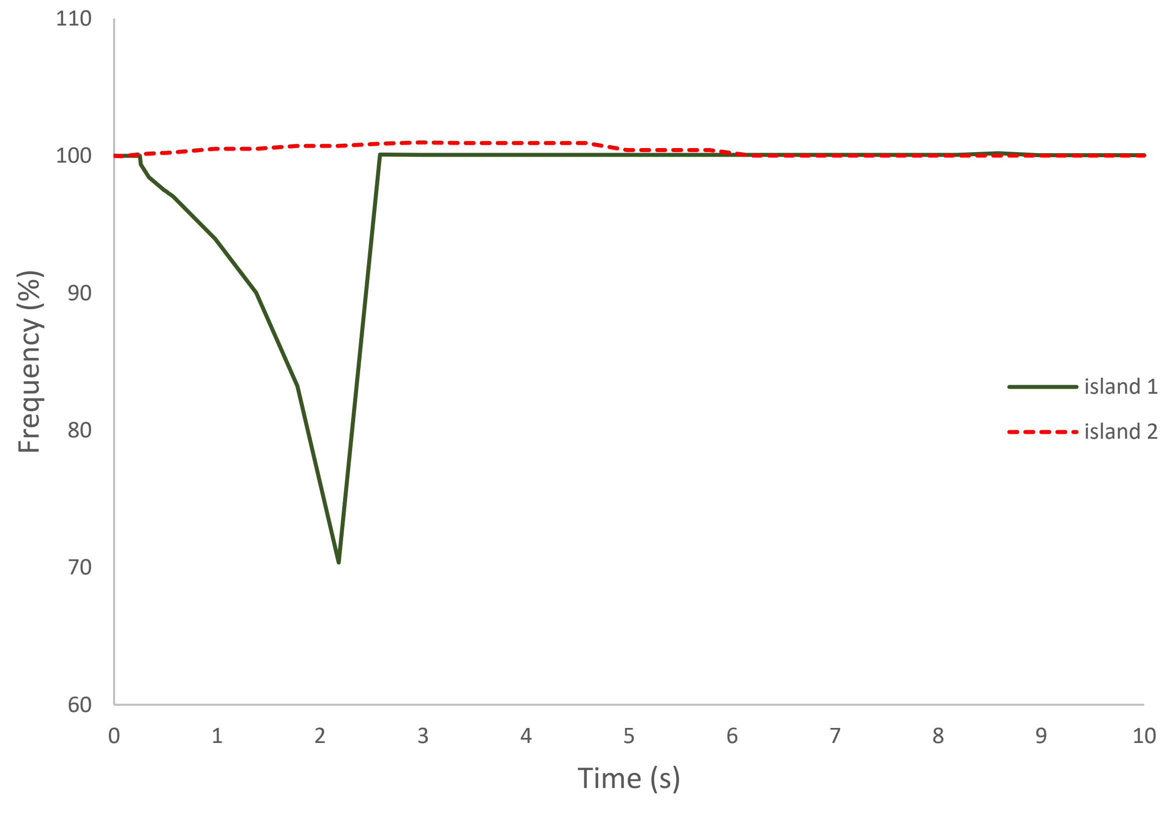


Figure III.27. Frequency curves for the island 1 and island 2 in the analyzed separation scenario 2 with the newly proposed scheme

**Table III.10.** Load shedding amount of the new UFLS scheme

| ***Scenario*** | ***Load shedding stages*** | ***Load shedding amount (MW)*** |
|---|---|---|
| ***Scenario 1*** | *First stage* | *2249.26* |
| | *Second stage* | *963,79* |
| | *Third stage* | *321.32* |
| | *Fourth Stage* | *321.32* |
| | *Total* | *3855,16* |
| ***Scenario 2*** | *First stage* | *1654,9* |
| | *Second stage* | *709.24* |
| | *Third stage* | *236.41* |
| | *Fourth Stage* | *236.41* |
| | *Total* | *2836.96* |

**Table III.11.** Undershoot frequency and time to frequency stability

| ***Scenario*** | ***Undershoot Frequency (Hz)*** | ***Time to Frequency Stability (seconds)*** |
|---|---|---|
| ***Scenario 1*** | *7.88* | *1.32* |
| ***Scenario 2 (Island 1)*** | *17.78* | *2.33* |

Figure III.26 demonstrates that the new implemented scheme effectively executed the Under Frequency Load Shedding (UFLS) process and successfully restored frequency stability within a short duration of 1.32 seconds.

On the other hand, the results obtained from the analysis of separation scenario 2 for island 1, as illustrated in Figure III.27, indicate that the proposed scheme was able to restore frequency stability in a relatively short duration of 2.33 seconds, in contrast to the performance observed in case C1.

As a result, the findings derived from the simulation results obtained from the two particular scenarios strongly suggest that the newly proposed scheme may serve as an efficient approach for restoring frequency stability, particularly in the context of a 30% penetration or less of renewable energy sources.

## III.4 Chapter Conclusion

In this chapter, we have provided an overview of the utilization of ETAP software for power system analysis and the creation of multiple scenarios to investigate transient stability. Our study focused on evaluating the performance of three existing load shedding schemes applied to the IEEE 39-bus system under different scenarios and case studies.

Our simulations have demonstrated that the Under Frequency Load Shedding (UFLS) process can effectively restore frequency stability in a tested system where all generators are synchronous machines. However, we have also identified limitations in the current UFLS process, particularly in scenarios with high penetration of Renewable Energy Sources (RES). These scenarios require alternative approaches to maintain frequency stability. To address this issue, we have proposed a new load shedding scheme based on comprehensive experiments. Our findings indicate that the newly proposed scheme is highly effective in restoring frequency stability, particularly in systems with RES penetration of 30% or less. The simulations have shown that the scheme successfully executes the UFLS process, leading to a relatively short duration of time for frequency restoration.

In conclusion, this chapter contributes to the broader knowledge and understanding of load shedding schemes, their performance in power systems, and the challenges and opportunities presented by the integration of renewable energy sources.

# General Conclusion

The stability of frequency in power systems is crucial to ensure reliable and efficient operation. Frequency stability refers to the ability of a power system to maintain a constant frequency within a narrow range, under normal and abnormal operating conditions. This thesis investigates the importance of Under Frequency Load Shedding (UFLS) in maintaining frequency stability in traditional power systems and power systems with a high penetration of renewable energy sources (RES).

The growing demand for sustainable energy sources and the adoption of low-carbon initiatives worldwide have resulted in significant changes to power systems. The increase in RES, such as solar and wind plants, has a significant impact on the frequency behavior of power systems due to their low inertia characteristics. To address this impact and challenges associated with maintaining frequency stability in power systems with high penetration of RES, the effectiveness of UFLS was investigated.

The simulation results obtained using ETAP software demonstrate the effectiveness of UFLS in maintaining frequency stability and preventing power system blackouts in emergency situations. The ETAP software was a valuable tool for simulating UFLS scenarios and analyzing the impact of different UFLS plans on power system stability and frequency stability. The simulation of different UFLS scenarios shows the impact of RES on the power system and compares it with traditional generation systems under various scenarios. The study also considers the effect of the amount of load in each stage and the response time of the frequency relay to suggest an effective UFLS plan that can restore frequency stability in power systems with a penetration of up to 30% from RES and avoid blackouts.

The findings of this thesis provide insights into the impact of RES on power system stability and demonstrate the importance of UFLS in maintaining frequency stability in power systems with high penetration of renewable energy sources. The study's results can help power system operators to design effective UFLS plans and ensure the reliable and efficient operation of power systems. These findings are important for the future of power systems, especially with the increasing demand for sustainable energy sources and the adoption of low-carbon initiatives worldwide.

## Recommendations for Future Research

In order to improve the effectiveness of under frequency load shedding (UFLS) schemes in maintaining power system stability during disturbances, we recommend exploring several key areas for future research:

1. Explore the use of intelligent load shedding techniques: Advances in machine learning and artificial intelligence can be leveraged to develop UFLS schemes that can dynamically adapt to changes in the power system and adjust load shedding levels accordingly.
2. Increase penetration of Distributed Generation (DG) and Renewable Energy Sources (RES): With the growing use of DG and RES, UFLS schemes need to be designed to effectively manage power imbalances resulting from their variability and unpredictability.
3. Explore new adaptive techniques for UFLS schemes: Adaptive techniques, such as fuzzy logic and neural networks, can be used to develop UFLS schemes that can adapt to changes in the power system and maintain frequency stability.
4. Implement UFLS schemes in large power systems: UFLS schemes are typically designed for smaller power systems, but their effectiveness in larger power systems remains untested. Future research should focus on developing UFLS schemes that can be implemented in larger power systems and evaluating their effectiveness.
5. Cybersecurity: The implementation of UFLS schemes should also consider cybersecurity aspects. Future research can investigate how to secure UFLS schemes from cyber-attacks, ensuring the reliability and safety of power systems.
6. Investigate the use of hybrid UFLS schemes: A combination of traditional UFLS schemes with newer techniques, such as intelligent load shedding and adaptive techniques, can provide better frequency stability in the power system.

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# *Appendices*

# *Appendix A*

## New-England Power System Data

The IEEE 39-bus system, also referred to as the 10-machine New-England Power System. This system consists of 39 buses, 10 synchronous generators, and 46 transmission lines.

### Generators

The parameters of the synchronous machines in the power system are presented in the following table. All values are given in per unit at a frequency of 60 Hz on a 100MVA base.

Table A.1: Parameters of the synchronous machines

| **Unit** No. | **H** (s) | **Ra** (pu) | **X'd** (pu) | **X'q** (pu) | **Xd** (pu) | **Xq** (pu) | **T'do** (s) | **T'qo** (s) | **Xl** (pu) |
|---|---|---|---|---|---|---|---|---|---|
| **1** | 500.0 | 0 | 0.006 | 0.008 | 0.02 | 0.019 | 7.0 | 0.7 | 0.003 |
| **2** | 30.3 | 0 | 0.0697 | 0.170 | 0.295 | 0.282 | 6.56 | 1.5 | 0.035 |
| **3** | 35.8 | 0 | 0.0531 | 0.0876 | 0.2495 | 0.237 | 5.7 | 1.5 | 0.0304 |
| **4** | 28.6 | 0 | 0.0436 | 0.166 | 0.262 | 0.258 | 5.69 | 1.5 | 0.0295 |
| **5** | 26.0 | 0 | 0.132 | 0.166 | 0.67 | 0.62 | 5.4 | 0.44 | 0.054 |
| **6** | 34.8 | 0 | 0.05 | 0.0814 | 0.254 | 0.241 | 7.3 | 0.4 | 0.0224 |
| **7** | 26.4 | 0 | 0.049 | 0.186 | 0.295 | 0.292 | 5.66 | 1.5 | 0.0322 |
| **8** | 24.3 | 0 | 0.057 | 0.0911 | 0.290 | 0.280 | 6.7 | 0.41 | 0.028 |
| **9** | 34.5 | 0 | 0.057 | 0.0587 | 0.2106 | 0.205 | 4.79 | 1.96 | 0.0298 |
| **10** | 42.0 | 0 | 0.031 | 0.008 | 0.1 | 0.069 | 10.2 | 0.0 | 0.0125 |

Table A.2: Line data

| Line Data | | | | | Transformer Tap | |
|---|---|---|---|---|---|---|
| **From Bus** | **To Bus** | **R** (pu) | **X** (pu) | **B** (pu) | **Magnitude** (pu) | **Angle** (°) |
| **1** | **2** | 0.0035 | 0.0411 | 0.6987 | 0.000 | 0.00 |
| **1** | **39** | 0.0010 | 0.0250 | 0.7500 | 0.000 | 0.00 |
| **2** | **3** | 0.0013 | 0.0151 | 0.2572 | 0.000 | 0.00 |
| **2** | **25** | 0.0070 | 0.0086 | 0.1460 | 0.000 | 0.00 |
| **3** | **4** | 0.0013 | 0.0213 | 0.2214 | 0.000 | 0.00 |
| **3** | **18** | 0.0011 | 0.0133 | 0.2138 | 0.000 | 0.00 |
| **4** | **5** | 0.0008 | 0.0128 | 0.1342 | 0.000 | 0.00 |
| **4** | **14** | 0.0008 | 0.0129 | 0.1382 | 0.000 | 0.00 |
| **5** | **6** | 0.0002 | 0.0026 | 0.0434 | 0.000 | 0.00 |
| **5** | **8** | 0.0008 | 0.0112 | 0.1476 | 0.000 | 0.00 |
| **6** | **7** | 0.0006 | 0.0092 | 0.1130 | 0.000 | 0.00 |
| **6** | **11** | 0.0007 | 0.0082 | 0.1389 | 0.000 | 0.00 |
| **7** | **8** | 0.0004 | 0.0046 | 0.0780 | 0.000 | 0.00 |
| **8** | **9** | 0.0023 | 0.0363 | 0.3804 | 0.000 | 0.00 |
| **9** | **39** | 0.0010 | 0.0250 | 1.2000 | 0.000 | 0.00 |
| **10** | **11** | 0.0004 | 0.0043 | 0.0729 | 0.000 | 0.00 |
| **10** | **13** | 0.0004 | 0.0043 | 0.0729 | 0.000 | 0.00 |
| **13** | **14** | 0.0009 | 0.0101 | 0.1723 | 0.000 | 0.00 |
| **14** | **15** | 0.0018 | 0.0217 | 0.3660 | 0.000 | 0.00 |
| **15** | **16** | 0.0009 | 0.0094 | 0.1710 | 0.000 | 0.00 |
| **16** | **17** | 0.0007 | 0.0089 | 0.1342 | 0.000 | 0.00 |
| **16** | **19** | 0.0016 | 0.0195 | 0.3040 | 0.000 | 0.00 |
| **16** | **21** | 0.0008 | 0.0135 | 0.2548 | 0.000 | 0.00 |
| **16** | **24** | 0.0003 | 0.0059 | 0.0680 | 0.000 | 0.00 |
| **17** | **18** | 0.0007 | 0.0082 | 0.1319 | 0.000 | 0.00 |
| **17** | **27** | 0.0013 | 0.0173 | 0.3216 | 0.000 | 0.00 |
| **21** | **22** | 0.0008 | 0.0140 | 0.2565 | 0.000 | 0.00 |
| **22** | **23** | 0.0006 | 0.0096 | 0.1846 | 0.000 | 0.00 |
| **23** | **24** | 0.0022 | 0.0350 | 0.3610 | 0.000 | 0.00 |
| **25** | **26** | 0.0032 | 0.0323 | 0.5130 | 0.000 | 0.00 |
| **26** | **27** | 0.0014 | 0.0147 | 0.2396 | 0.000 | 0.00 |
| **26** | **28** | 0.0043 | 0.0474 | 0.7802 | 0.000 | 0.00 |
| **26** | **29** | 0.0057 | 0.0625 | 1.0290 | 0.000 | 0.00 |
| **28** | **29** | 0.0014 | 0.0151 | 0.2490 | 0.000 | 0.00 |
| **12** | **11** | 0.0016 | 0.0435 | 0.0000 | 1.006 | 0.00 |
| **12** | **13** | 0.0016 | 0.0435 | 0.0000 | 1.006 | 0.00 |
| **6** | **31** | 0.0000 | 0.0250 | 0.0000 | 1.070 | 0.00 |
| **10** | **32** | 0.0000 | 0.0200 | 0.0000 | 1.070 | 0.00 |

*Continued on next page*

Table A.2: Continued from previous page

| **Line Data** | | | | | **Transformer Tap** | |
|---|---|---|---|---|---|---|
| **From Bus** | **To Bus** | **R** (pu) | **X** (pu) | **B** (pu) | **Magnitude** (pu) | **Angle** (°) |
| **19** | **33** | 0.0007 | 0.0142 | 0.0000 | 1.070 | 0.00 |
| **20** | **34** | 0.0009 | 0.0180 | 0.0000 | 1.009 | 0.00 |
| **22** | **35** | 0.0000 | 0.0143 | 0.0000 | 1.025 | 0.00 |
| **23** | **36** | 0.0005 | 0.0272 | 0.0000 | 1.000 | 0.00 |
| **25** | **37** | 0.0006 | 0.0232 | 0.0000 | 1.025 | 0.00 |
| **2** | **30** | 0.0000 | 0.0181 | 0.0000 | 1.025 | 0.00 |
| **29** | **38** | 0.0008 | 0.0156 | 0.0000 | 1.025 | 0.00 |
| **19** | **20** | 0.0007 | 0.0138 | 0.0000 | 1.060 | 0.00 |

Table A.3: Power and voltage set points

| **Bus** | **Type** | **Voltage** | **Load** | | **Generator** | | |
|---|---|---|---|---|---|---|---|
| | | (pu) | MW | MVar | MW | MVar | Unit No. |
| **1** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **2** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **3** | **PQ** | - | 322.0 | 2.4 | 0.0 | 0.0 | |
| **4** | **PQ** | - | 500.0 | 184.0 | 0.0 | 0.0 | |
| **5** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **6** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **7** | **PQ** | - | 233.8 | 84.0 | 0.0 | 0.0 | |
| **8** | **PQ** | - | 522.0 | 176.0 | 0.0 | 0.0 | |
| **9** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **10** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **11** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **12** | **PQ** | - | 7.5 | 88.0 | 0.0 | 0.0 | |
| **13** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **14** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **15** | **PQ** | - | 320.0 | 153.0 | 0.0 | 0.0 | |
| **16** | **PQ** | - | 329.0 | 32.3 | 0.0 | 0.0 | |
| **17** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **18** | **PQ** | - | 158.0 | 30.0 | 0.0 | 0.0 | |
| **19** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **20** | **PQ** | - | 628.0 | 103.0 | 0.0 | 0.0 | |
| **21** | **PQ** | - | 274.0 | 115.0 | 0.0 | 0.0 | |
| **22** | **PQ** | - | 0.0 | 0.0 | 0.0 | 0.0 | |
| **23** | **PQ** | - | 247.5 | 84.6 | 0.0 | 0.0 | |
| **24** | **PQ** | - | 308.6 | -92.0 | 0.0 | 0.0 | |
| **25** | **PQ** | - | 224.0 | 47.2 | 0.0 | 0.0 | |
| **26** | **PQ** | - | 139.0 | 17.0 | 0.0 | 0.0 | |
| **27** | **PQ** | - | 281.0 | 75.5 | 0.0 | 0.0 | |
| **28** | **PQ** | - | 206.0 | 27.6 | 0.0 | 0.0 | |
| **29** | **PQ** | - | 283.5 | 26.9 | 0.0 | 0.0 | |
| **30** | **PV** | 1.0475 | 0.0 | 0.0 | 250.0 | - | Gen10 |
| **31** | **PV** | 0.9820 | 9.2 | 4.6 | - | - | Gen2 |
| **32** | **PV** | 0.9831 | 0.0 | 0.0 | 650.0 | - | Gen3 |
| **33** | **PV** | 0.9972 | 0.0 | 0.0 | 632.0 | - | Gen4 |
| **34** | **PV** | 1.0123 | 0.0 | 0.0 | 508.0 | - | Gen5 |
| **35** | **PV** | 1.0493 | 0.0 | 0.0 | 650.0 | - | Gen6 |
| **36** | **PV** | 1.0635 | 0.0 | 0.0 | 560.0 | - | Gen7 |
| **37** | **PV** | 1.0278 | 0.0 | 0.0 | 540.0 | - | Gen8 |
| **38** | **PV** | 1.0265 | 0.0 | 0.0 | 830.0 | - | Gen9 |
| **39** | **PV** | 1.0300 | 1104.0 | 250.0 | 1000.0 | - | Gen1 |

# *Appendix B*

## Load Flow Results

Table B.1: Bus results

| **Bus ID** | **Nominal kV** | **Type** | **Voltage** (%) | **MW Loading** | **Mvar Loading** |
|---|---|---|---|---|---|
| **Bus 1** | 345 | Load | 102,54 | 131,575 | 169,675 |
| **Bus 2** | 345 | Load | 102 | 466,336 | 196,417 |
| **Bus 3** | 345 | Load | 101,83 | 346,914 | 182,245 |
| **Bus 4** | 345 | Load | 101,51 | 515,192 | 257,97 |
| **Bus 5** | 345 | Load | 101,45 | 726,792 | 106,979 |
| **Bus 6** | 345 | Load | 101,44 | 1054,595 | 208,8 |
| **Bus 7** | 345 | Load | 101,42 | 327,601 | 94,876 |
| **Bus 8** | 345 | Load | 101,45 | 577,277 | 313,125 |
| **Bus 9** | 345 | Load | 102,38 | 39,813 | 311,332 |
| **Bus 10** | 345 | Load | 101,58 | 649,518 | 135,895 |
| **Bus 11** | 345 | Load | 101,52 | 293,725 | 136,422 |
| **Bus 12** | 345 | Load | 100,22 | 7,533 | 88,383 |
| **Bus 13** | 345 | Load | 101,57 | 355,718 | 69,996 |
| **Bus 14** | 345 | Load | 101,61 | 352,113 | 144,103 |
| **Bus 15** | 345 | Load | 101,85 | 331,936 | 298,789 |
| **Bus 16** | 345 | Load | 102,1 | 866,774 | 460,853 |
| **Bus 17** | 345 | Load | 101,99 | 212,34 | 130,908 |
| **Bus 18** | 345 | Load | 101,91 | 176,513 | 103,714 |
| **Bus 19** | 345 | Load | 102,64 | 628,702 | 297,756 |
| **Bus 20** | 345 | Load | 98,22 | 605,85 | 204,208 |
| **Bus 21** | 345 | Load | 102,12 | 601,481 | 123,233 |
| **Bus 22** | 345 | Load | 102,3 | 649,575 | 146,402 |
| **Bus 23** | 345 | Load | 102,42 | 605,708 | 294,784 |
| **Bus 24** | 345 | Load | 102,18 | 345,881 | 158,937 |
| **Bus 25** | 345 | Load | 102,06 | 538,231 | 93,121 |
| **Bus 26** | 345 | Load | 102,03 | 400,985 | 61,497 |
| **Bus 27** | 345 | Load | 101,94 | 292,021 | 78,461 |
| **Bus 28** | 345 | Load | 102,15 | 345,464 | 44,429 |
| **Bus 29** | 345 | Load | 102,24 | 824,469 | 91,274 |
| **Bus 30** | 22 | Gen. | 100 | 250 | 31,095 |
| **Bus 31** | 22 | SWNG | 98,2 | 774,492 | 56,025 |
| **Bus 32** | 22 | Gen. | 98,31 | 650 | 207,505 |
| **Bus 33** | 22 | Gen. | 99,72 | 632 | 262,835 |
| **Bus 34** | 22 | Gen. | 102 | 508 | 260,601 |
| **Bus 35** | 22 | Gen. | 100 | 650 | 38,615 |
| **Bus 36** | 22 | Gen. | 106,35 | 560 | 410,777 |
| **Bus 37** | 22 | Gen. | 102,78 | 540 | 24,301 |
| **Bus 38** | 22 | Gen. | 102,65 | 830 | 199,133 |
| **Bus 39** | 345 | Gen. | 103 | 1171,234 | 729,781 |

Table B.2: Branch results

| ID | From Bus | To Bus | MW Flow | Mvar Flow | % PF |
|---|---|---|---|---|---|
| **Line 1** | Bus 9 | Bus 39 | 26,805 | 347,23 | 7,7 |
| **Line 2** | Bus 1 | Bus 39 | 198,267 | -195,594 | -71,19 |
| **Line 3** | Bus 2 | Bus 25 | 291,731 | -100,297 | -94,57 |
| **Line 4** | Bus 25 | Bus 26 | 13,62 | 17,473 | 61,48 |
| **Line 5** | Bus 26 | Bus 29 | 182,742 | 34,155 | 98,3 |
| **Line 6** | Bus 26 | Bus 28 | 130,948 | 27,397 | 97,88 |
| **Line 7** | Bus 28 | Bus 29 | 345,569 | 47,162 | 99,08 |
| **Line 8** | Bus 1 | Bus 2 | 198,489 | -201,668 | -70,15 |
| **Line 9** | Bus 8 | Bus 9 | 26,578 | 348,337 | 7,61 |
| **Line 10** | Bus 5 | Bus 8 | 462,767 | -61,778 | -99,12 |
| **Line 11** | Bus 4 | Bus 5 | 35,768 | 60,548 | 50,86 |
| **Line 12** | Bus 2 | Bus 3 | 342,499 | 130,614 | 93,44 |
| **Line 13** | Bus 3 | Bus 4 | 282,304 | 195,356 | 82,23 |
| **Line 14** | Bus 6 | Bus 7 | 285,563 | -22,038 | -99,7 |
| **Line 15** | Bus 7 | Bus 8 | 45,965 | -106,822 | -39,53 |
| **Line 18** | Bus 5 | Bus 6 | 427,031 | -122,434 | -96,13 |
| **Line 19** | Bus 10 | Bus 11 | 106,829 | 69,303 | 83,89 |
| **Line 20** | Bus 10 | Bus 13 | 101,23 | 49,447 | 89,85 |
| **Line 21** | Bus 4 | Bus 14 | 266,471 | 52,39 | 98,12 |
| **Line 22** | Bus 14 | Bus 15 | 372,367 | 143,487 | 93,31 |
| **Line 23** | Bus 15 | Bus 16 | 703,85 | 302,338 | 91,88 |
| **Line 24** | Bus 16 | Bus 17 | 545,208 | 106,698 | 98,14 |
| **Line 25** | Bus 17 | Bus 27 | 108,466 | 14,398 | 99,13 |
| **Line 26** | Bus 26 | Bus 27 | 182,877 | 63,881 | 94,41 |
| **Line 27** | Bus 6 | Bus 11 | 103,87 | 26,676 | 96,86 |
| **Line 28** | Bus 21 | Bus 22 | 601,963 | 131,334 | 97,7 |
| **Line 29** | Bus 22 | Bus 23 | 47,611 | -145,481 | -31,1 |
| **Line 30** | Bus 23 | Bus 24 | 346,444 | 66,524 | 98,21 |
| **Line 31** | Bus 16 | Bus 24 | 24,88 | 164,011 | 15 |
| **Line 32** | Bus 16 | Bus 19 | 1317,439 | 290,202 | 97,66 |
| **Line 33** | Bus 16 | Bus 21 | 316,604 | 12,656 | 99,92 |
| **Line 34** | Bus 17 | Bus 18 | 436,554 | 95,54 | 97,69 |
| **Line 35** | Bus 3 | Bus 18 | 272,75 | 66,555 | 97,15 |
| **Line 36** | Bus 13 | Bus 14 | 105,834 | 93,949 | 74,79 |
| **T 1** | Bus 25 | Bus 37 | 540 | 28,222 | 99,86 |
| **T 2** | Bus 29 | Bus 38 | 830 | 204,961 | 97,08 |
| **T 3** | Bus 22 | Bus 35 | 650 | 46,678 | 99,74 |
| **T 4** | Bus 2 | Bus 30 | 250 | 38,147 | 98,86 |
| **T 5** | Bus 6 | Bus 31 | 608,724 | -171,148 | -96,27 |
| **T 6** | Bus 10 | Bus 32 | 650 | 222,284 | 94,62 |
| **T 7** | Bus 20 | Bus 34 | 508 | 211,408 | 92,32 |
| **T 8** | Bus 19 | Bus 33 | 819,325 | 277,443 | 94,72 |
| **T 9** | Bus 19 | Bus 20 | 505,381 | 159,032 | 95,39 |
| **T 10** | Bus 23 | Bus 36 | 560 | 415,184 | 80,33 |
| **T 11** | Bus 13 | Bus 12 | 4,6 | 45,347 | 10,09 |
| **T 12** | Bus 12 | Bus 11 | 2,953 | 44,244 | 6,66 |

Table B.3: Loads

| **ID** | **Terminal Bus** | **Rating** | **Rated kV** | **MW** | **Mvar** | **% PF** | **% Loading** | **V terminal** (%) |
|---|---|---|---|---|---|---|---|---|
| **Lump 1** | Bus 39 | 1131,952 MVA | 345 | 1171,234 | 265,225 | 97,53 | 103 | 103 |
| **Lump 2** | Bus 8 | 550,872 MVA | 345 | 535,162 | 180,438 | 94,76 | 101,3 | 101,25 |
| **Lump 3** | Bus 7 | 248,432 MVA | 345 | 239,51 | 86,052 | 94,11 | 101,2 | 101,21 |
| **Lump 4** | Bus 31 | 10,286 MVA | 22 | 8,872 | 4,436 | 89,44 | 98,2 | 98,2 |
| **Lump 5** | Bus 10 | 636,391 MVA | 345 | 643,907 | 105,609 | 98,68 | 101,3 | 101,26 |
| **Lump 6** | Bus 23 | 261,527 MVA | 345 | 259,008 | 88,429 | 94,64 | 102,3 | 102,3 |
| **Lump 7** | Bus 21 | 297,155 MVA | 345 | 285,05 | 119,638 | 92,21 | 102 | 102 |
| **Lump 8** | Bus16 | 327 MVA | 345 | 338,835 | 27,66 | 99,67 | 102 | 101,96 |
| **Lump 9** | Bus 15 | 354,696 MVA | 345 | 330,822 | 158,174 | 90,22 | 101,7 | 101,68 |
| **Lump 10** | Bus 28 | 207,841 MVA | 345 | 214,56 | 28,747 | 99,11 | 102,1 | 102,06 |
| **Lump 11** | Bus 27 | 290,966 MVA | 345 | 291,343 | 78,279 | 96,57 | 101,8 | 101,82 |
| **Lump 12** | Bus 18 | 160,823 MVA | 345 | 163,621 | 31,067 | 98,24 | 101,8 | 101,76 |
| **Lump 13** | Bus 3 | 322,009 MVA | 345 | 332,82 | 2,481 | 100 | 101,7 | 101,67 |
| **Lump 14** | Bus 25 | 228,919 MVA | 345 | 232,878 | 49,071 | 97,85 | 102 | 101,96 |
| **Lump 15** | Bus 26 | 140,036 MVA | 345 | 144,391 | 17,659 | 99,26 | 101,9 | 101,92 |
| **Lump 16** | Bus 29 | 284,773 MVA | 345 | 295,845 | 28,071 | 99,55 | 102,2 | 102,15 |
| **Lump 17** | Bus 24 | 322,021 MVA | 345 | 321,337 | -95,795 | -95,83 | 102 | 102,04 |
| **Lump 18** | Bus 12 | 88,319 MVA | 345 | 7,489 | 87,876 | 8,49 | 99,9 | 99,93 |
| **Lump 19** | Bus 4 | 532,781 MVA | 345 | 513,003 | 188,785 | 93,85 | 101,3 | 101,29 |
| **Lump 32** | Bus 16 | 66,304 MVA | 345 | 68,704 | 5,608 | 99,67 | 102 | 101,96 |

Table B.4: Sources

| **Terminal Bus** | **Type** | **Rating** | **Rated kV** | **MW** | **Mvar** | **% PF** |
|---|---|---|---|---|---|---|
| **Bus 39** | Synchronous | 1000 MW | 345 | 1000 | 792,941 | 78,36 |
| **Bus 31** | Synchronous | - | 22 | 617,986 | -69,125 | -99,38 |
| **Bus 32** | Synchronous | 650 MW | 22 | 650 | 222,284 | 94,62 |
| **Bus 33** | Synchronous | 632 MW | 22 | 632 | 277,443 | 94,72 |
| **Bus 34** | Synchronous | 508 MW | 22 | 508 | 211,408 | 92,32 |
| **Bus 35** | Synchronous | 650 MW | 22 | 650 | 46,678 | 99,74 |
| **Bus 36** | Synchronous | 560 MW | 22 | 560 | 415,184 | 80,33 |
| **Bus 37** | Synchronous | 540 MW | 22 | 540 | 28,222 | 99,86 |
| **Bus 38** | Synchronous | 830 MW | 22 | 830 | 204,961 | 97,08 |
| **Bus 30** | Synchronous | 250 MW | 22 | 250 | 38,147 | 98,86 |

# ***Appendix c***

## The single-line diagram simulation for Case with RES – C1