Voltage Stability Analysis for Power System with Dynamic Load

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1 Introduction

Voltage stability is fundamental for the reliable operation of electrical power systems. It is defined as the system's ability to maintain acceptable voltages at all buses both under normal operating conditions and after a disturbance or contingency, such as the loss of a transmission line. Voltage instability often originates at weak buses—those with high sensitivity dV/dQ—and can escalate into a voltage collapse, a process in which falling voltage leads to increased current demand, further voltage drops, and ultimately a progressive decay of the system voltage.

Voltage collapse is essentially a "vicious cycle" of falling voltage triggered by a contingency. This drop leads to dynamic loads (such as motors) drawing more current to maintain their power output, which, in turn, causes even greater voltage drop (due to increased losses in transmission lines). The system does not effectively compensate for this cascade, leading to progressive voltage decay until a collapse occurs.

A key element that can aggravate this process is the action of Under-Load Tap Changers (ULTCs). Although designed to restore load-side voltage, the tap reduction lowers the equivalent impedance seen from the transmission side, thereby increasing the current drawn and accelerating the instability loop. Generator reactive limits, load characteristics, and the dynamics of excitation systems also play decisive roles.

This project focuses on analyzing the mechanism of voltage instability and collapse by addressing its fundamental causes, including the destabilizing action of ULTCs, generator limits, and the behavior of dynamic loads. To achieve this, the considered power system is structured into two main scenarios : scenario 1 will assess the system's vulnerability by considering three different load levels at buses 8 and 11, identifying how total demand influences stability. Subsequently, scenario 2 will investigate the critical case where the load at bus 8 is modeled as an induction motor, seeking to quantify the direct influence of dynamic loads on the time to collapse.

The main objective of these simulations is to examine the evolution of critical stability variables to understand the robustness of the system. This includes monitoring the voltages at key buses (7, 10, and 11), as well as a detailed analysis of the performance and operational limits of generators 2 and 3, recording their terminal voltages, reactive power outputs, and field currents. The results obtained will provide essential information on the system's transient response to a disturbance and will underscore the decisive role of control equipment, such as ULTCs, in dynamic voltage stability.

2 Objectives

2.1 General objective

Evaluate the transient voltage stability of the power system following a contingency, focusing on the destabilizing impact of dynamic loads.

2.2 Specific objectives

— Study the modeling and simulation of power system components (synchronous machines, excitation systems, etc.) using Matlab/Simulink to construct the complete simulation environment.
— Analyze the voltage stability of the system through time-domain simulations, comparing system response under dynamic load.
— Implement and execute defined simulation scenarios to determine the system's stability margin and critical response time under different load and dynamic conditions.
— Interpret time-domain responses of critical variables (bus voltages, reactive power outputs, generator limits) to identify and quantify the determining factors (ULTC action, Q limits, etc.) that accelerate voltage collapse.

3 Fundamental Concepts of Voltage Stability

3.1 Relationship Between Voltage and Reactive Power

At the core of voltage stability lies the relationship between bus voltage magnitude and reactive power. For a system to be voltage stable, an increase in reactive power injection at a bus must lead to an increase in voltage magnitude at that bus. This condition can be expressed qualitatively by a positive sensitivity of voltage with respect to reactive power. When this sensitivity becomes negative, the system enters an unstable operating region.

Reactive power is required to support electric and magnetic fields in system components such as transmission lines, transformers, and motors. As reactive power demand increases and available supply becomes constrained, voltage magnitudes decrease. This interaction becomes particularly pronounced under heavy loading conditions, making voltage stability a limiting factor in power transfer capability.

3.2 Transmission System Characteristics

The characteristics of interest are the relationships between the transmitted power (P_R), receiving end voltage (V_R), and the reactive power injection (Q_i).

Transmission networks have a decisive influence on voltage stability due to their inherent consumption of reactive power. As active power transfer through a transmission line increases, reactive power losses increase rapidly because line current increases. This effect is especially significant for long transmission lines and heavily loaded corridors.

For a simple system supplying a load through a transmission line (as shown in Figure 1), there exists a maximum transferable power beyond which the receiving-end voltage drops sharply.

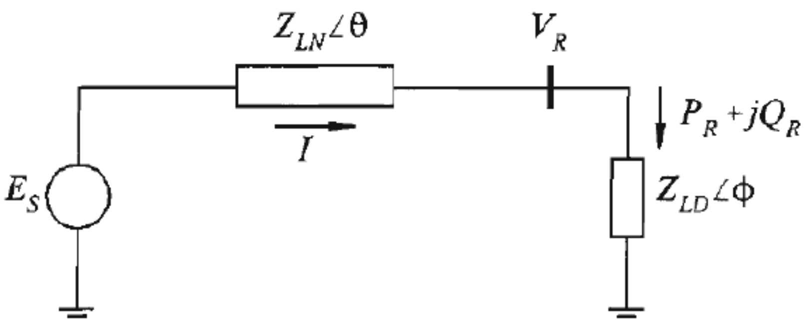

FIGURE 1 – A simple radial system

The variations of line current I, receiving-end voltage V_R, and delivered active power PR with respect to load demand are illustrated in Figure 2. The results correspond to a case where the transmission impedance angle is 10, and the load power factor is 0.95. To ensure that the conclusions are independent of the absolute value of the line impedance, the quantities are expressed in normalized form.

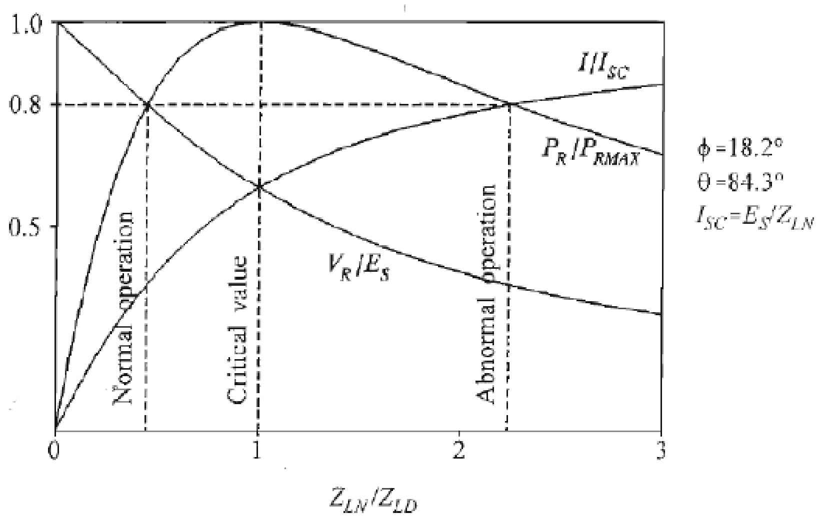

FIGURE 2 – Receiving end voltage, current, and power as a function of load demand

As the load demand increases, which corresponds to a decrease in load impedance, the active power delivered to the load initially increases rapidly. With further increase in demand, the rate of increase in P_R slows down until a maximum value is reached, beyond which the transmitted power begins to decrease. This behavior indicates the existence of a maximum transferable active power through a given impedance supplied by a constant-voltage source. Maximum power transfer occurs when the magnitude of the voltage drop across the line becomes equal to the receiving-end voltage, corresponding to a load-to-line impedance ratio of unity. The operating condition at this point represents the limit of acceptable system operation, and the associated values of current and receiving-end voltage are referred to as critical values.

For any delivered power level below the maximum transferable power, two distinct operating points may exist, corresponding to two different values of load impedance. This phenomenon is illustrated in Figure 2. for a delivered power of $P_R = 0.8$. The operating point on the left-hand side of the curve corresponds to normal operating conditions. In contrast, the operating point on the right-hand side is characterized by significantly higher current and substantially lower receiving-end voltage, indicating a stressed and undesirable operating state.

When the load demand exceeds the maximum transferable power, stable control of power by adjusting the load becomes impossible. In this region, an increase in load admittance results in a reduction of delivered power. The subsequent voltage behavior depends strongly on the voltage–load characteristic. For a constant-admittance load, the system may settle at a new steady-state operating point with a reduced voltage level. However, if the load is supplied through a transformer equipped with an under-load tap-changing mechanism, the tap changer will attempt to restore the load voltage. This action effectively reduces the load impedance seen from the transmission system, further increasing current and deepening the voltage drop. The resulting feedback process leads to a continuous decline in voltage, which is identified as voltage instability.

An alternative and widely used representation of this phenomenon is obtained by plotting the relationship between receiving-end voltage and delivered active power for different load power factors, while maintaining a constant source voltage, as shown in Figure 3. The locus of critical operating points is indicated by dashed curves. Only operating points located above these critical points correspond to stable and acceptable system operation.

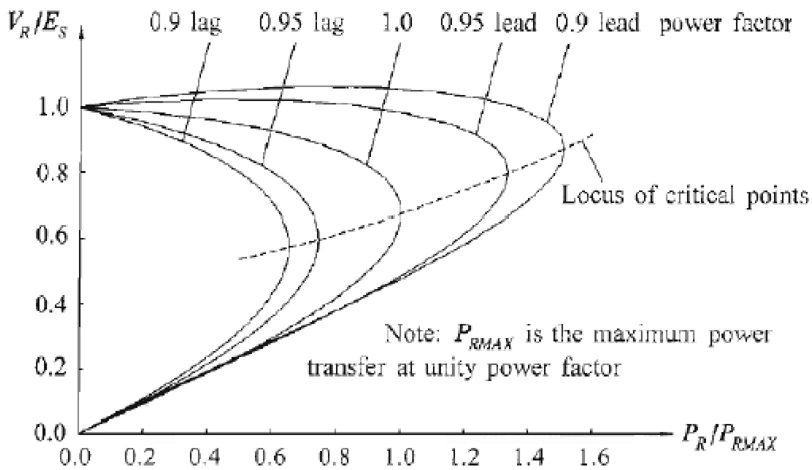

FIGURE 3 – $V_R - P_R$ characteristics of the system in Figure 1

The figure illustrates the relationship between the receiving-end voltage V_R and the delivered active power P_R for the system shown in Figure 1. The curve demonstrates the nonlinear dependence of bus voltage on the level of power transferred to the load. At low power levels, the receiving-end voltage remains close to its nominal value, indicating normal and stable operating conditions.

As the transmitted power increases, the receiving-end voltage gradually decreases due to increased current flow and associated voltage drops across the transmission impedance. This region corresponds to stable system operation, where small changes in load result in predictable and controllable voltage variations. The slope of the curve in this region reflects the system's ability to supply reactive power and maintain voltage regulation.

At higher power transfer levels, the curve reaches a critical point, often referred to as the voltage stability limit or nose point. Beyond this point, further increases in load demand cannot be supported by the system. Any attempt to increase delivered power results in a rapid decline in receiving-end voltage. Operating points below this critical voltage are unstable and cannot be sustained under normal system controls.

The lower portion of the $V_R - P_R$ characteristic represents unstable equilibrium points. In this region, small disturbances can cause large voltage deviations, leading to voltage instability or collapse. Therefore, only operating points located above the critical point on the curve correspond to satisfactory and secure operating conditions.

This figure highlights the importance of maintaining adequate voltage stability margins and avoiding operation near the critical region, particularly in heavily loaded or weak transmission systems.

It also demonstrates that the shape of the power–voltage (P–V) characteristic is strongly influenced by the load power factor. Variations in power factor significantly affect the maximum transferable active power and the overall voltage stability margin of the system.

For lagging power factor conditions, which correspond to predominantly inductive loads, the P–V curve contracts and the maximum transferable power is reduced. Inductive loads absorb reactive power from the system, increasing reactive power demand and aggravating voltage drops. As a result, the system reaches its voltage stability limit at lower levels of power transfer.

In contrast, for leading power factor conditions associated with capacitive loads, the P–V curve expands and the maximum transferable power increases. Capacitive loads supply reactive power to the network, supporting voltage levels and improving the system's ability to sustain higher power transfers without instability.

The collection of peak points from the P–V curves corresponding to different power factors forms a boundary that represents the voltage stability limit of the system. Operating points beyond this boundary are unstable regardless of the load power factor.

These characteristics highlight the critical role of reactive power support in maintaining voltage stability. Adequate reactive power compensation, reflected by leading power factor conditions, is essential for extending voltage stability margins and ensuring secure system operation.

3.3 Generator Characteristics and Voltage Control

3.3.1 Role of Synchronous Generators in Voltage Support

Synchronous generators are the primary sources of controllable reactive power in power systems. Through their excitation systems, generators regulate terminal voltage by adjusting the field current, thereby controlling reactive power output. Under normal conditions, generators operate as voltage-controlled buses and contribute to maintaining system voltages within acceptable limits.

Automatic voltage regulators (AVRs) respond rapidly to voltage deviations by adjusting excitation. This fast response makes generators highly effective in counteracting short-term voltage fluctuations following disturbances.

3.3.2 Generator Reactive Power Limits

Despite their effectiveness, generators are subject to physical and thermal limits that constrain their reactive power capability. These limits arise from stator current constraints, rotor field current constraints, and stability considerations. When reactive power output reaches these limits, generators can no longer maintain their voltage set-points.

Once a generator reaches its excitation limit, it effectively transitions from voltage control mode to reactive power control mode. This change has important implications for voltage stability, as the generator can no longer support declining voltages in the surrounding network. In voltage stability studies, neglecting excitation limits can lead to unrealistic results, as generators may appear to supply unlimited reactive power.

3.3.3 Illustrative Example of the Impact of Generator Excitation Limits on Voltage Stability

To demonstrate the effect of losing generator voltage control capability, consider the system illustrated in Figure 4. The system comprises a large load supplied radially from a strong source, represented as an infinite bus, with an intermediate generating unit providing partial load supply and regulating the voltage at an intermediate bus.

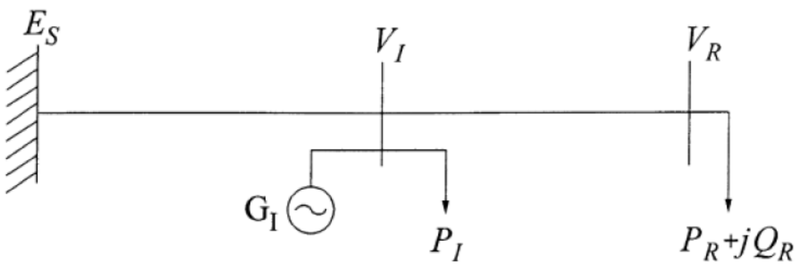

FIGURE 4 – Generator with AVR example

As long as the intermediate generator is able to maintain voltage regulation, the relationship between bus voltage and transmitted power is represented by Curve 1 in

Figure 5. Under this condition, the generator adjusts its excitation to supply the required reactive power, thereby sustaining the bus voltage over a wide range of operating points.

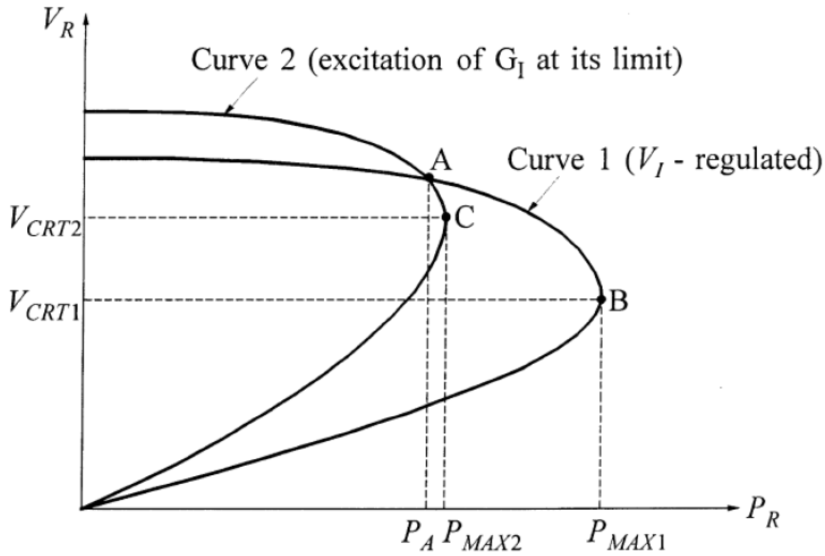

FIGURE 5 – The $V_R - P_R$ characteristics of a generator

When the generator reaches its field current limit, its ability to regulate voltage is lost. The intermediate bus voltage is no longer controlled and becomes dependent on system conditions. In this case, the voltage–power characteristic shifts to Curve 2 in Figure 5, reflecting a reduced voltage stability margin and a more stressed operating condition.

An operating point such as Point A, although identical in terms of transmitted power and voltage magnitude, exhibits significantly different stability characteristics depending on the generator's control capability. When operating on Curve 1, the system remains relatively stable due to active voltage regulation. However, when the same operating point lies on Curve 2, the system is considerably less stable as voltage support from the generator is no longer available.

These observations highlight the critical importance of preserving generator voltage control capability for maintaining voltage stability. Furthermore, they demonstrate that voltage stability cannot be assessed solely based on the proximity of bus voltage to its nominal value. A system may appear to operate at an acceptable voltage level while still being close to instability if reactive power reserves and voltage control margins are exhausted.

3.4 Load Characteristics and Their Impact on Voltage Stability

The behavior of system loads plays a crucial role in determining voltage stability. Unlike generators and transmission networks, loads are not passive elements ; their power consumption often depends on voltage magnitude and system dynamics. Consequently, the way loads respond to voltage variations can either mitigate voltage instability or significantly accelerate it.

3.4.1 Static Load Models

Static load models describe the steady-state relationship between voltage and power consumption without considering time-dependent dynamics. Common static representations include constant impedance, constant current, and constant power models.

Constant impedance loads draw power proportional to the square of the voltage magnitude. As voltage decreases, both current and power consumption decrease, which tends to relieve system stress and support voltage stability. Constant current loads draw current independent of voltage, resulting in power consumption that decreases linearly with voltage. These load types generally exhibit stabilizing behavior under voltage disturbances.

In contrast, constant power loads are particularly unfavorable from a voltage stability perspective. Such loads attempt to maintain constant active and reactive power consumption regardless of voltage variations. When the voltage decreases, the current drawn by the load must increase to satisfy the power requirement. This increase in current leads to higher transmission losses and greater reactive power demand, causing further voltage reduction. This feedback mechanism makes constant power loads a major contributor to voltage instability.

3.4.2 Dynamic Load Models

Dynamic loads exhibit time-dependent behavior that significantly influences voltage stability, especially during and after disturbances. Induction motors are the most important dynamic load type in power systems, as they constitute a large portion of industrial and commercial demand.

During a voltage drop, induction motors draw increased reactive current in order to maintain electromagnetic torque. This increased reactive power demand exacerbates the voltage decline and may lead to a rapid reduction in voltage if sufficient reactive support is not available. If the voltage depression persists, motors may decelerate or stall, resulting in very high current draw and further aggravating system stress.

The recovery behavior of dynamic loads is also critical. After a disturbance, motors attempt to reaccelerate, which can cause a delayed increase in reactive power demand. This phenomenon can prevent voltage recovery and may trigger short-term voltage instability even after the initial fault has been cleared.

3.4.3 Load Recovery and Voltage Instability

Many loads exhibit recovery characteristics, meaning that after a voltage disturbance, power consumption gradually returns to its pre-disturbance level. While load recovery is desirable from a service perspective, it can be detrimental to voltage stability. As load power demand recovers, reactive power demand increases, potentially pushing the system beyond its voltage stability limit.

This delayed increase in demand can interact with other system controls, such as generator excitation limits and under-load tap-changing transformers (ULTC). If these controls are unable to supply the required reactive power, voltage may continue to decline over time, leading to long-term voltage instability.

3.4.4 Impact on Voltage Stability Assessment

Accurate representation of load characteristics is essential for meaningful voltage stability analysis. Simplified load models that neglect voltage dependency or dynamic behavior may fail to capture critical instability mechanisms. In systems with a high proportion of induction motor loads or electronically controlled loads, dynamic load modeling becomes particularly important.

The interaction between load behavior, reactive power availability, and voltage control mechanisms ultimately determines whether a system can withstand disturbances without experiencing voltage instability or collapse.

3.5 Reactive Power Compensation Devices and Voltage Stability

Reactive power compensation devices are widely employed in power systems to support voltage levels and enhance voltage stability margins. Since voltage instability is fundamentally associated with insufficient reactive power supply or inadequate reactive power transfer capability, compensation devices play a critical role in maintaining acceptable voltage profiles, particularly under heavily loaded or disturbed operating conditions.

3.5.1 Shunt Compensation Devices

Shunt capacitors are among the most commonly used reactive power compensation devices due to their simplicity and low cost. By injecting reactive power locally, shunt capacitors reduce the reactive power demand on transmission lines and generators, thereby improving voltage levels at load buses.

However, the reactive power output of shunt capacitors is proportional to the square of the voltage magnitude. As system voltage declines, the amount of reactive power supplied by these devices decreases, reducing their effectiveness during severe voltage depressions. Consequently, while shunt capacitors are effective for steady-state voltage support, their contribution to voltage stability under stressed conditions is limited.

3.5.2 Synchronous Condensers

Synchronous condensers are synchronous machines operated without a mechanical load and are capable of supplying or absorbing reactive power through excitation control. Unlike shunt capacitors, synchronous condensers can provide reactive power support over a wider voltage range and maintain effectiveness during voltage depressions.

Due to their rotating inertia and controllable excitation, synchronous condensers contribute to both short-term and long-term voltage stability. However, their relatively high cost and maintenance requirements have limited their widespread deployment compared to static compensation devices.

3.5.3 Power Electronic-Based Compensation Devices

Power electronic-based devices, such as Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs), provide fast and flexible reactive power control. These devices dynamically adjust reactive power output in response to voltage changes, making them highly effective in supporting voltage during transient and dynamic conditions.

SVCs utilize thyristor-controlled reactors and capacitors to regulate reactive power, while STATCOMs employ voltage-source converters to inject or absorb reactive power independent of system voltage magnitude. As a result, STATCOMs retain their effectiveness even during deep voltage depressions, making them particularly valuable in weak networks and heavily loaded systems.

3.5.4 Impact on Voltage Stability

Reactive power compensation devices improve voltage stability by reducing voltage drops, increasing reactive power reserves, and enhancing the system's ability to withstand disturbances. Proper placement of these devices on electrically weak buses can significantly increase voltage stability margins and delay or prevent voltage collapse.

However, reactive power compensation alone cannot guarantee voltage stability. Its effectiveness depends on coordination with generator excitation systems, load characteristics, and transformer tap-changing mechanisms. Poorly coordinated or insufficient compensation may fail to prevent instability, particularly when generators reach excitation limits or when load recovery mechanisms dominate system behavior.

3.5.5 Summary

Reactive power compensation devices are essential tools for maintaining voltage stability in modern power systems. While shunt capacitors provide economical steady-state support, dynamic devices such as synchronous condensers, SVCs, and STATCOMs offer superior performance under stressed and transient conditions. Effective voltage stability enhancement requires appropriate selection, placement, and coordination of compensation devices within the broader system control framework.

4 Voltage Collapse

Voltage collapse is the end result of severe voltage instability and represents a condition in which the power system is no longer able to maintain acceptable voltage levels. It is typically characterized by a rapid and uncontrollable decline in voltage that leads to partial or widespread interruption of the electric power supply. Voltage collapse is not caused by a single event but rather by a sequence of interacting factors that progressively weaken the system's ability to support load demand.

4.1 Mechanism of Voltage Collapse

The process leading to voltage collapse usually begins with a disturbance such as a transmission line outage, a generator outage, or a significant increase in load demand. This initial event causes a reduction in voltage at one or more buses, particularly in electrically weak areas of the network. In response, loads draw increased current and reactive power, intensifying voltage drops across transmission elements.

Generators and reactive power compensation devices attempt to counteract the voltage decline by supplying additional reactive power. Automatic voltage regulators increase generator excitation, while compensation devices inject reactive power locally. If sufficient reactive power reserves are available, the system may stabilize at a new operating point.

However, when reactive power reserves become exhausted or generator excitation limits are reached, further voltage support is no longer possible. At this stage, voltage recovery mechanisms lose effectiveness, and the system enters a self-reinforcing cycle in which decreasing voltage causes increasing reactive power demand, leading to further voltage decline. This positive feedback process ultimately results in voltage collapse.

4.2 Role of Load Behavior

Load characteristics play a critical role in the voltage collapse process. Constant power loads and dynamic loads such as induction motors tend to increase current draw as voltage decreases. This behavior accelerates the depletion of reactive power reserves and aggravates voltage instability.

In particular, stalled or decelerating induction motors draw large amounts of reactive power, causing abrupt voltage drops. Load recovery mechanisms can further exacerbate the situation by gradually restoring power demand following an initial disturbance, thereby increasing reactive power requirements at a time when system reserves are already limited.

4.3 Influence of Under-Load Tap-Changing Transformers

Under-load tap-changing transformers (ULTCs) are designed to maintain acceptable voltage levels at load buses by adjusting transformer tap ratios. During a voltage depression, ULTCs act to raise the load-side voltage, which is beneficial under normal operating conditions.

Under stressed conditions, however, ULTC action can contribute to voltage collapse. By increasing the tap ratio, the ULTC reduces the effective load impedance seen from the upstream network, resulting in increased current flow and higher reactive power demand. This additional stress may further reduce upstream voltages, intensifying system-wide voltage decline and promoting long-term voltage instability.

4.4 Short-Term and Long-Term Voltage Collapse

Voltage collapse may occur over different time scales depending on the dominant system dynamics. Short-term voltage collapse is associated with fast phenomena such as generator excitation response, induction motor dynamics, and power electronic controls. These events typically unfold over a time frame of seconds.

Long-term voltage collapse involves slower mechanisms such as ULTC operation, generator over-excitation limiters, and load recovery characteristics. These processes may develop over several minutes, making long-term voltage collapse particularly challenging to detect and mitigate in real-time operation.

4.5 Prevention of Voltage Collapse

Preventing voltage collapse requires maintaining adequate reactive power reserves and ensuring effective coordination among system control mechanisms. This includes proper generator excitation control with realistic limiters, strategic placement of reactive power compensation devices, appropriate ULTC control strategies, and accurate load modeling.

Operating the system with sufficient voltage stability margins and avoiding operation near critical conditions are essential for ensuring secure and reliable power system performance.

4.6 Classification of Voltage Stability

Voltage stability phenomena can be classified based on the dominant time scale of the system dynamics involved. This classification is important because different mechanisms govern voltage behavior over different time horizons, and appropriate analysis and control strategies depend on the type of voltage stability under consideration. Voltage stability is commonly categorized into short-term and long-term voltage stability.

4.6.1 Short-Term Voltage Stability

Short-term voltage stability refers to the system's ability to maintain acceptable voltage levels following small perturbations over a time frame ranging from a few cycles to several seconds. This form of voltage stability is dominated by fast system dynamics, including generator excitation systems, induction motor behavior, electronically controlled loads, and power electronic compensation devices.

Following a disturbance such as a fault or sudden load change, automatic voltage regulators act rapidly to restore voltage by increasing generator excitation and reactive power output. At the same time, dynamic loads, particularly induction motors, may draw increased reactive current in response to voltage depressions. The interaction between fast reactive power supply and rapidly increasing reactive power demand determines whether voltage recovers or continues to decline.

Short-term voltage instability may occur if reactive power support is insufficient or if dynamic loads dominate system behavior. This type of instability often manifests as a rapid voltage collapse shortly after the disturbance and may occur even before slower control mechanisms, such as transformer tap changers, have time to respond.

4.6.2 Long-Term Voltage Stability

Long-term voltage stability involves slower system dynamics and typically evolves over a period of several minutes. It is associated with mechanisms such as under-load tap-changing transformers, generator over-excitation limiters, thermostatic load recovery, and operator control actions.

In long-term voltage stability scenarios, the system may initially appear stable following a disturbance. Voltages may recover partially due to fast excitation control and reactive power compensation. However, as slower control mechanisms act to restore load voltages or power consumption, reactive power demand gradually increases. This may push generators toward their excitation limits and exhaust available reactive power reserves.

Under-load tap-changing transformers play a particularly important role in long-term voltage stability. By adjusting tap ratios to maintain load-side voltage, ULTCs may unintentionally increase upstream reactive power demand and transmission losses, thereby contributing to progressive voltage decline and eventual instability.

4.6.3 Interaction Between Short-Term and Long-Term Stability

Short-term and long-term voltage stability phenomena are not independent and may interact in complex ways. A system that survives the initial transient following a disturbance may still experience voltage collapse minutes later due to the action of slower control mechanisms. Conversely, poor short-term voltage performance may trigger long-term instability by delaying voltage recovery and increasing stress on reactive power sources.

Effective voltage stability assessment therefore requires consideration of both time scales. Accurate modeling of fast dynamics and slow control actions is essential to capture the full range of voltage instability mechanisms.

4.6.4 Summary

The classification of voltage stability into short-term and long-term categories provides a structured framework for understanding voltage instability phenomena. Short-term voltage stability is dominated by fast dynamic responses, while long-term voltage stability is influenced by slower control and load recovery mechanisms. Recognizing these distinctions is essential for selecting appropriate analysis techniques and designing effective voltage control strategies.

5 Voltage Stability Analysis Methods

Voltage stability analysis aims to assess the ability of a power system to maintain acceptable voltage levels under varying operating conditions and following disturbances. Since voltage instability can develop through both steady-state limitations and dynamic interactions, a combination of static and dynamic analysis techniques is required for a comprehensive assessment. Each method provides different insights and serves distinct purposes in system planning and operation.

5.1 Static Voltage Stability Analysis

Static voltage stability analysis focuses on steady-state system behavior and evaluates how close an operating point is to voltage collapse. These methods assume that system dynamics have settled and that voltages and power flows remain constant over time. Static analysis is widely used in planning studies to identify weak buses and assess voltage stability margins. One of the most common static tools is power–voltage (P–V) curve analysis. In this approach, system loading is gradually increased while solving the steady-state power flow equations. The resulting P–V curve illustrates the relationship between bus voltage magnitude and active power demand. The maximum point on the curve, known as the nose point, represents the voltage stability limit. Operating points close to this limit indicate reduced voltage stability margin.

Another important static technique is reactive power–voltage (Q–V) analysis. Q–V curves are obtained by injecting or absorbing reactive power at a selected bus and observing the corresponding voltage response. These curves provide insight into the local reactive power margin and the sensitivity of voltage to reactive power variations. Buses with steep Q–V characteristics or small reactive power margins are considered weak from a voltage stability perspective.

Although static methods are computationally efficient and useful for identifying vulnerable operating conditions, they do not capture time-dependent effects such as generator excitation limits, load dynamics, or transformer tap-changing actions. As a result, static analysis alone may not be sufficient for systems where dynamic phenomena dominate voltage behavior.

5.2 Dynamic Voltage Stability Analysis

Dynamic voltage stability analysis examines the time-domain response of the power system following disturbances. This approach accounts for the dynamic behavior of generators, excitation systems, loads, reactive power compensation devices, and transformer controls. Dynamic analysis is essential for understanding the sequence of events that may lead to voltage instability or collapse.

Time-domain simulations are typically used to perform dynamic voltage stability studies. In these simulations, a disturbance such as a line outage, load increase, or fault is applied, and the evolution of bus voltages, reactive power flows, and control actions is observed over time. This method allows the interaction between fast dynamics (such as excitation systems and induction motor behavior) and slow dynamics (such as ULTC operation and load recovery) to be accurately represented.

Dynamic analysis is particularly important in systems with significant induction motor loads, tight reactive power margins, or extensive use of under-load tap-changing transformers. These systems may appear stable under static analysis but experience voltage collapse due to delayed control actions or exhaustion of reactive power reserves.

5.3 Modeling Requirements for Voltage Stability Studies

Accurate voltage stability analysis requires detailed and realistic modeling of system components that influence reactive power balance and voltage control. This includes generator excitation systems with appropriate limiters, dynamic load models, transformer tap-changing mechanisms, and reactive power compensation devices.

Simplified models that neglect excitation limits or assume static load behavior may lead to overly optimistic conclusions regarding system stability. Therefore, model fidelity must be selected carefully based on the objectives of the study and the time scale of interest.

5.4 Application to the Studied System

The voltage stability concepts discussed in this chapter directly apply to the studied system. The interaction between generator excitation limits, ULTC action between buses 10 and 11, dynamic load behavior, and transmission contingencies forms the basis for the voltage instability phenomena observed in the simulations. The results demonstrate how local voltage control mechanisms, while beneficial under normal conditions, may contribute to system-wide instability when operating near system limits.

6 Model design

The power system to be analyzed and modeled is an 11-bus test system (shown in Figure 6) designed for time-domain voltage stability analysis, this test system is based on the described in reference [1]. All component parameters are provided in the Per Unit (pu) system, based on a System Power Base (S_{base}) of 100 MVA.To establish a consistent physical framework for simulation, the primary generation buses (1, 2, and 3) are defined with a nominal base of 24 kV, while the transmission backbone (Buses 5 through 10) operates on a 400 kV base. The system utilizes a total of six (6) three-phase transformers (T1 through T6) to step up or step down voltages across the network.

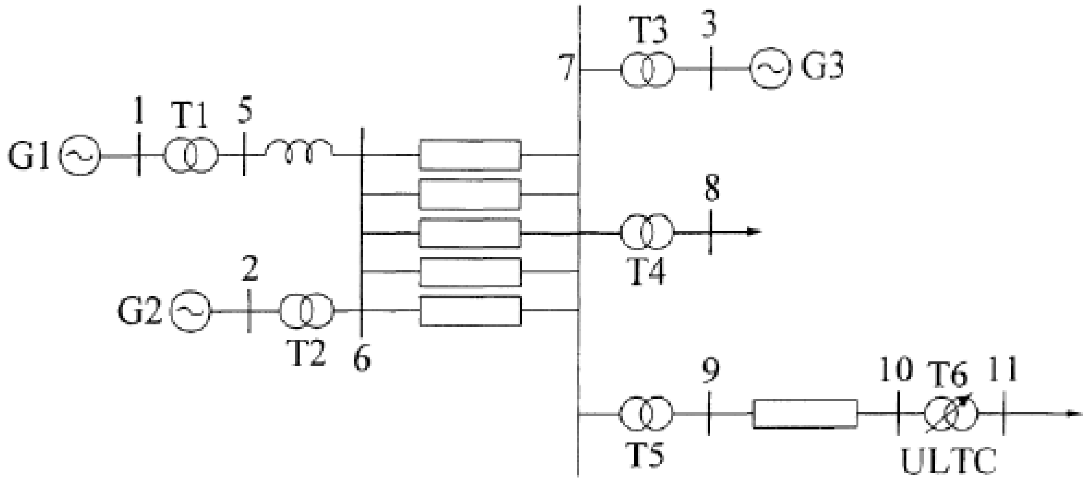

FIGURE 6 – Test System

Beyond the static network topology, the complete model incorporates the dynamic implementation of synchronous machines, their respective control systems (AVR and OXL), transmission lines, and time-dependent loads. Each component's parameterization and its translation from theoretical pu values to the simulation environment are detailed in the following subsections.

6.1 Generators and Controls Models

6.1.1 G1 : Infinite Bus

The Infinite Bus (G1) is an ideal representation of a very large, external power system. Its defining characteristic is that its voltage magnitude and frequency remain constant regardless of the active (P) or reactive (Q) power exchanged with the local system.

The ideal source in Simscape is the Three-Phase Source block as shown in Figure 7. To emulate the behavior of an infinite bus within the Simscape environment, the internal impedance is set to a negligible value, ensuring that Bus 1 acts as the system's slack bus and maintains a constant voltage profile throughout the transient event. Aditionally, a grounded-Y (Yg) connection is assumed to provide a solid neutral reference for the network.

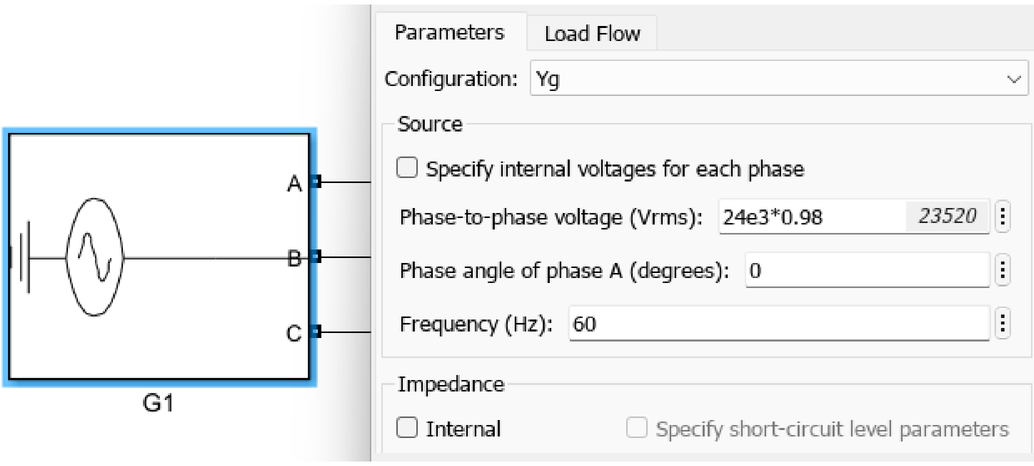

FIGURE 7 – Simscape G1 block

6.1.2 G2 & G3 : Synchronous machines

The Synchronous Machine pu Standard (Figure 8) block was chosen over the fundamental block for two key reasons. Firstly, the Standard block directly integrates subtransient, transient, and steady-state parameters, which are essential for the required detailed dynamic analysis and are readily available for this study. Secondly, the fundamental block requires specific variables and parameters that are not known, making the Standard block the more appropriate choice for accurate modeling based on the accessible data.

The parametrization of the Simscape Synchronous Machine pu Standard block (for G2 and G3) is listed in Table 1, all other settings were left at their default values.

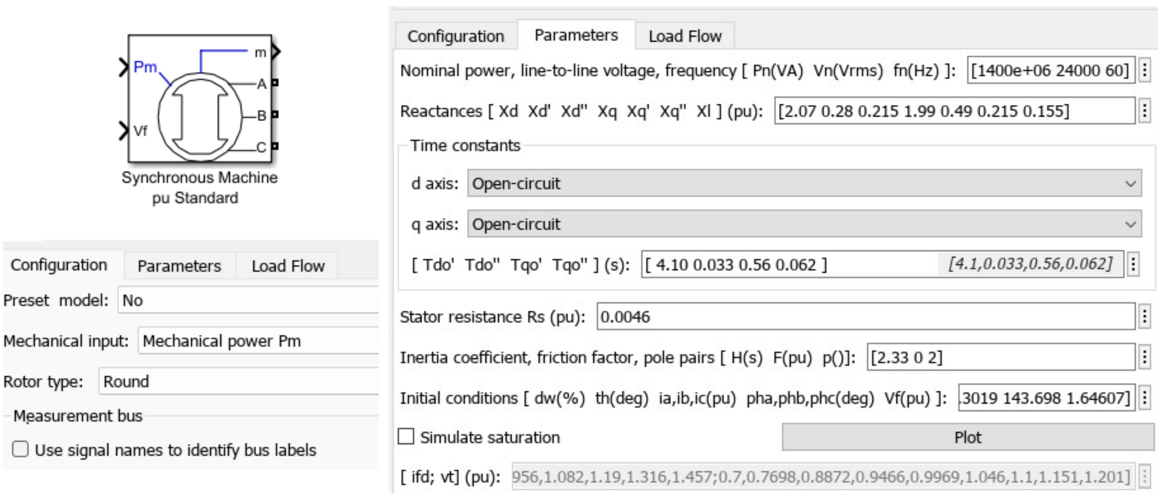

FIGURE 8 – Simscape Synchronous Machine pu Standard block for G2 and G3

Table 1 – Machine parameters given

Symbol	Parameter	Value (pu)
R_a	Armature (stator) resistance	0.0046
X_l	Leakage reactance	0.155
X_d	Synchronous reactance (d-axis)	2.07
X_q	Synchronous reactance (q-axis)	1.99
X'_d	Transient reactance (d-axis)	0.28
X''_d	Subtransient reactance (d-axis)	0.215
X'_q	Transient reactance (q-axis)	0.49
X''_q	Subtransient reactance (q-axis)	0.215
T'_{d0}	Open-circuit transient time constant (d-axis)	4.10
T''_{d0}	Open-circuit subtransient time constant (d-axis)	0.033
T'_{q0}	Open-circuit transient time constant (q-axis)	0.56
T''_{q0}	Open-circuit subtransient time constant (q-axis)	0.062
H	Inertia constant	2.09 (G2) 2.33 (G3)

6.1.3 Excitation system

The synchronous machine model was integrated with its Excitation System (AVR) to implement automatic voltage regulation, as shown in the Figure 9. The terminal V_d and V_q from the synchronous machine are fed back to the AVR, which compares the measured voltage with a constant Reference Voltage ($V_{ref} = 1$) and outputs the necessary Field Voltage (V_f). For both machine 2 and machine 3 the exciters have a gain of 400 and the sensing circuit-time constant of 0.02 seconds, the other parameters are the default values.

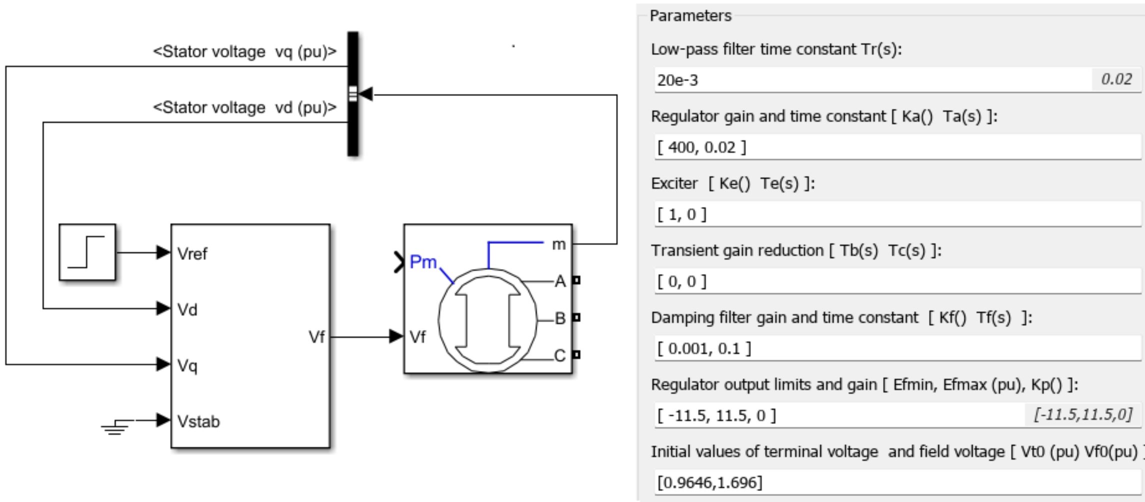

Figure 9 – Excitation system

An overexcitation limiter (OXL) was implemented only for Generator 3 following the characteristic shown in Figure 10 The limiter activates when the field current exceeds $I_{fd_{max1}} = 3.02pu$, integrating with gain $K_1 = 0.248$ and output gain $K_2 = 12.6$. It resets when the current falls below $I_{fd_{max2}} = 4.60pu$. This prevents sustained overexcitation and mimics the generator's thermal protection.

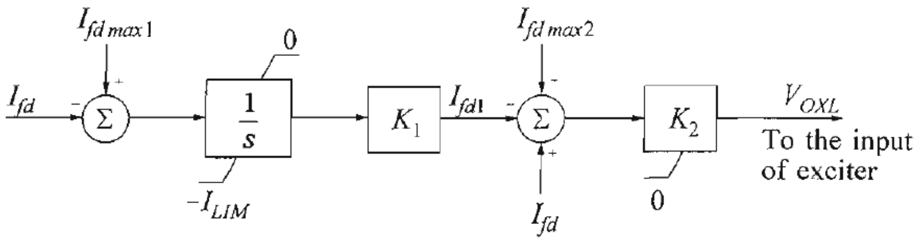

FIGURE 10 – Block diagram of OXL

6.1.4 Turbine-governor system

The Hydraulic Turbine and Governor block (Figure 11) for generators G2 and G3 was implemented to regulate active power (P) and system frequency. This control loop is crucial as it ensures mechanical power (P_m) stability, which is assumed to be maintained throughout the transient event. The model utilizes the default parameters of the Simulink block and the value of 0.8 p.u. for P_r (rated mechanical power).

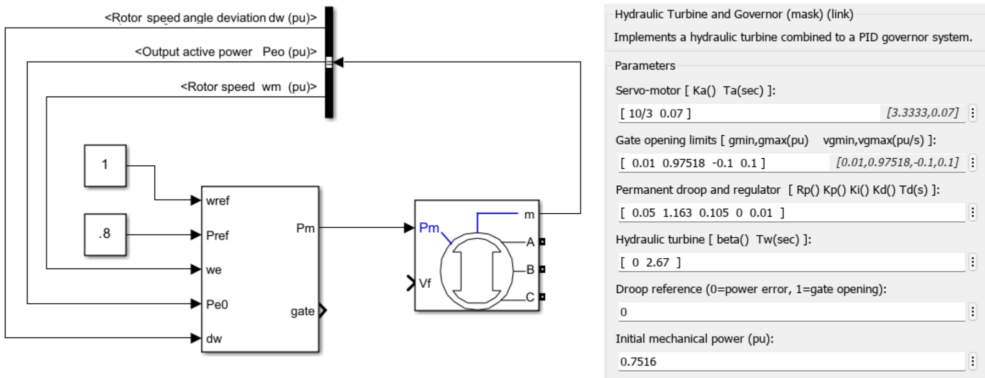

FIGURE 11 – Turbine-governor system

6.1.5 Integrated Synchronous Machine Control Scheme

Figure 12 illustrates the complete control scheme implemented for the synchronous generator within the Simulink environment. This model integrates the two primary control loops : active power (frequency control) given by the hydraulic turbine and governor system and reactive power (voltage control) given by the excitation system block.

This integrated model, which combines the synchronous machine with its excitation control loops (AVR) and turbine-governor (TG), is the final result of Work Plan 1.

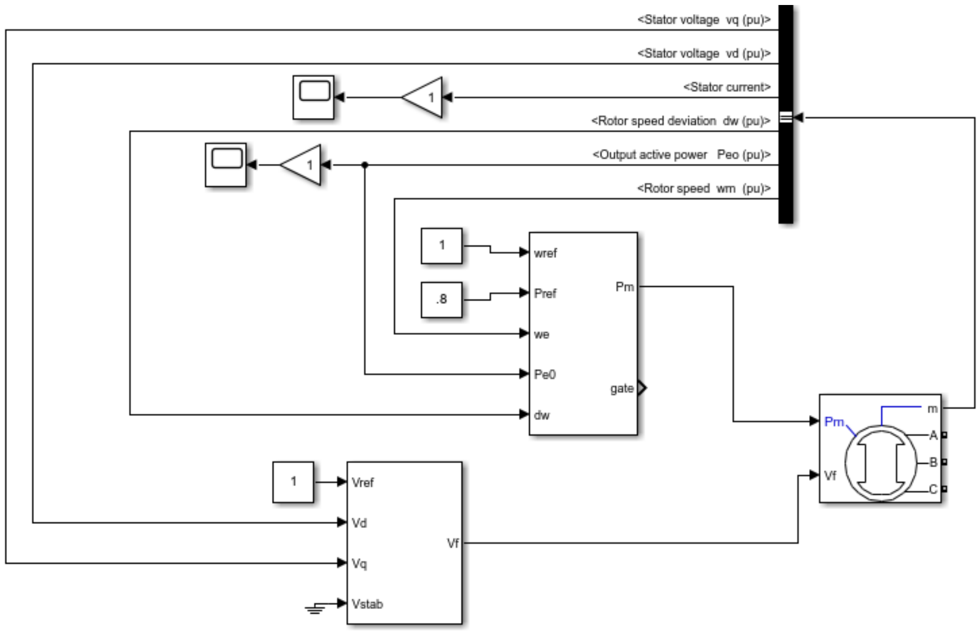

FIGURE 12 – Integrated Synchronous Machine Control Scheme

To ensure a stable start for the time-domain simulation, the initial conditions for G2 and G3 (such as power angle and field voltage) are determined using the *Machine Initialization* tool within the Powergui block, aligning the machines' starting points with the steady-state load flow results.

To facilitate the construction of the 11-bus system (Work Plan 2), this complete control scheme is encapsulated within a Simulink Modular Subsystem. This modular approach allows for easily copying and connecting generation units G2 and G3 to the rest of the system, simplifying the top-level view of the complete model by hiding the internal complexity of the dynamic control loops and directly connecting the subsystem's output terminals (terminals A, B, C) to transformers T2 and T3 and, therefore, to the 11-bus network, enabling the rapid integration of passive components. This subsystem becomes the fundamental dynamic generation unit for modeling the complete system.

6.2 Transformers

The six (6) transformers are divided into two functional groups : fixed and dynamic. Their parameters are provided in Table 2 on a system base of 100 MVA.

However, for the physical implementation in the Simulink environment, the nominal power (S_{nom}) for each unit was assumed based on the maximum expected power flow from the nearest generator or the connected load level. This ensures that the transformers operate within a realistic range without reaching premature saturation, while the per-unit impedances remain consistent with the 100 MVA system base.

To preserve the correct physical impedance, the per-unit reactances must be referred to the nominal power of each transformer block in Simulink. The nominal power of the

TABLE 2 – Transformers parameters given

Transformer	R_{pu}	X_{pu}	Ratio	
T1	0.0000	0.0020	0.8857	
T2	0.0000	0.0045	0.8857	
T3	0.0000	0.0125	0.9024	
T4	0.0000	0.0030	1.0664	
T5	0.0000	0.0026	1.0800	
T6	0.0000	0.0010	0.9750	(load level 1)
			0.9938	(load level 2)
			1.0000	(load level 3)

transformers was chosen according to the rating of the associated generator or load (e.g., 2200 MVA for T2, 1400 MVA for T3). The conversion follows :

$$X_{\text{new}} = X_{\text{old}} \cdot \frac{S_{\text{nom}}}{100},$$

where X_{old} is the value from Table 2 and S_{nom} is the nominal power entered in the block.

6.2.1 Standard Transformers (T1 to T5)

These transformers have a fixed ratio and are used for voltage coupling between the different buses. They will be implemented using the Three-Phase Transformer (Two-Winding) block in Simulink with Delta-Yg conection for step-up transformers and Yg-Delta for step-down.

The values needed for this block are :

— **Nominal power :** As described above, chosen according to the connected equipment.

— **Frequency :** 60 [Hz].

— **Windings parameters (V Ph-Ph(Vrms), R(pu), L(pu)) :**

- The primary voltage (V_1) and secondary voltage (V_2) are defined based on the network zone.he ratio provided in Table 2 represents the per-unit transformation factor $a = V_{1,\text{pu}}/V_{2,\text{pu}}$, which already accounts for the physical base-voltage relationship between the two sides. Therefore, the secondary voltage for every transformer is obtained as $V_2 = V_{base,secondary}/Ratio$, where $V_{base,secondary}$ is the voltage base of the secondary side in the actual network (400 kV for all transmission-side windings). The primary voltage V_1 is set directly to the base voltage of the primary side (24 kV for generator-side windings, 400 kV for transmission-side windings).
- $R_{pu} = 0$ for all these units
- The converted leakage reactance X_{new} is split equally between the two windings : $L_1 = L_2 = 0.5\, X_{\text{new}}$.

— Magnetization resistance and Magnetization inductance : set as default values.

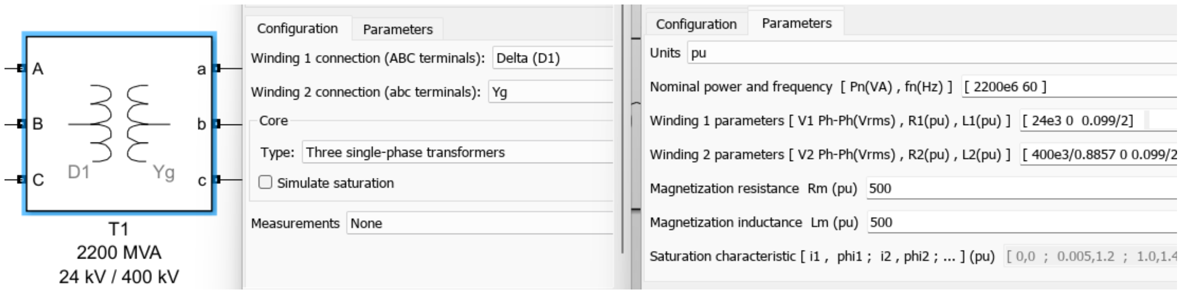

FIGURE 13 – Simscape - Transformer block

6.2.2 On-Load Tap Changer (T6 - ULTC)

Transformer T6, connecting Bus 10 to Bus 11, is an On-Load Tap Changer (ULTC) designed to maintain the voltage magnitude at the load Bus 11 within a specific deadband ($\pm1\%$), despite variations in system loading.

Unlike standard transformers, the T6 model incorporates a discrete control logic that emulates real-world mechanical tap changers. The ULTC is implemented using the Three-Phase OLTC Regulating Transformer (Phasor Type) block. Its key parameters are :

- **Voltage step per tap :** 0.00625 pu (5/8%).
- **Tap range :** ±16 steps.
- **Initial tap position :** Calculated from the ratio a as

$$\text{Tap} = \frac{a-1}{0.00625}.$$

  Thus,
  - Load Level 1 : $a = 0.9750 \Rightarrow \text{Tap} = -4$
  - Load Level 2 : $a = 0.9938 \Rightarrow \text{Tap} = -1$
  - Load Level 3 : $a = 1.0000 \Rightarrow \text{Tap} = 0$
- **Control logic :** The regulator measures the voltage magnitude at bus 11 and compares it with a reference value V_{ref} pu within a deadband of ±0.01 pu ($\pm1\%$).
- **Time delays :** The first tap movement is delayed by 30 s; subsequent steps occur every 5 s.
- **Winding configuration :** Both windings are connected in grounded-Y (Yg) with no phase shift.

This block is critical for the stability study, as the ULTC's attempt to restore load voltage increases the reactive power demand on the transmission network, potentially leading to voltage instability or collapse under heavy load conditions.

6.3 Transmission lines

All transmission lines are modeled using the Nominal PI Section Model to account for the longitudinal impedance and shunt capacitance. The Three-Phase PI Section Line block in Simulink is used for implementation. The parameters of these lines are given in the Table 3.

TABLE 3 – Lines parameters given

Line	$\mathbf{R_{pu}}$	$\mathbf{X_{pu}}$	$\mathbf{B_{pu}}$
5 - 6	0.0000	0.0040	0.0000
6 - 7	0.0015	0.0288	1.1730
9 - 10	0.0010	0.0030	0.0000

The analysis and simulation of electric power networks in Simulink when employing the three-phase RLC transmission line block, require all network parameters to be expressed in their corresponding physical units of Ohms, Henrys, and Farads per kilometer ($\Omega/\text{km}, \text{H}/\text{km}, \text{F}/\text{km}$). The system's initial data of the transmission lines, are provided in Per Unit (pu) values. Therefore, the essential first step in modeling is to perform a base conversion, utilizing the local Base Impedance ($\mathbf{Z}_{\text{base}}$) for each network section. This Z_{base} is calculated from the system power base ($\mathbf{S}_{\text{base}} = \mathbf{100}$ MVA) and the local bus voltage base ($\mathbf{V}_{\text{base}}$). The key conversion formulas are :

— Resistance and Reactance :

$$R(\Omega) = R_{\text{pu}} \cdot Z_{\text{base}} \quad \text{and} \quad X(\Omega) = X_{\text{pu}} \cdot Z_{\text{base}}$$

— Inductance : calculated using the system frequency (f) where :

$$L(\text{H}) = X/(2\pi f)$$

— Susceptance :

$$B(\text{S}) = B_{\text{pu}}/Z_{\text{base}}$$

— Capacitance : calculated from the shunt susceptance B_{pu} :

$$C(\text{F}) = B/(2\pi f)$$

The configuration of the Three-Phase PI Section Line block in Simulink requires the input of parameter vectors representing both positive-sequence (1) and zero-sequence (0) values. Since the provided dataset only specifies positive-sequence parameters (standard for power flow studies), it is necessary to estimate the zero-sequence components based on typical transmission line geometries and grounding characteristics. For this study, the following empirical relationships are adopted to ensure the model's consistency during unbalanced or ground-related phenomena :

— **Resistance ($[r_1 \ r_0]$) :** The zero-sequence resistance is estimated as three times the positive-sequence value ($r_0 \approx 3r_1$), accounting for the higher impedance of the ground return path.

— **Inductance ($[l_1 \ l_0]$) :** Similarly, the zero-sequence inductance is assumed to be three times the positive-sequence inductance ($l_0 \approx 3l_1$).

— **Capacitance ($[c_1 \ c_0]$) :** The zero-sequence capacitance is typically lower than the positive-sequence due to the electric field distribution ; a factor of 0.6 is applied ($c_0 \approx 0.6c_1$).

Based on the system topology and the location of the transformers, the network is divided into distinct voltage zones. The detailed calculations for each line are presented below :

1. The line 5-6 is assumed to operate within the 400 kV section of the network, which maintains a constant base impedance.

$$Z_{base} = \frac{(V_{base})^2}{S_{base}} = \frac{(400 \times 10^3 \text{ V})^2}{100 \times 10^6 \text{ VA}} = \mathbf{1600\ \Omega}$$

$$X_L(\Omega/\text{km}) = X_{\text{pu}} \cdot Z_{\text{base}} = 0.0040 \cdot 1600\ \Omega = \mathbf{6.4\ \Omega}/\text{km}$$

$$L_{5-6}(\text{H/km}) = \frac{X1}{2\pi f} = \frac{6.4}{2\pi(60)} \approx \mathbf{0.016976}\ \text{H/km}$$

2. The lines between 6 and 7 are assumed to operate within the 400 kV section of the network, which maintains a constant base impedance.

$$Z_{base} = 1600\ \Omega$$

$$R_{6-7}(\Omega/km) = R_{pu} \cdot Z_{base} = 0.0015 \cdot 1600\ \Omega = \mathbf{2.4\ \Omega/km}$$

$$X_L(\Omega/km) = X_{pu} \cdot Z_{base} = 0.0288 \cdot 1600\ \Omega \approx 46.08\ \Omega/km$$

$$L_{6-7}(H/km) = \frac{X1}{2\pi f} = \frac{46.08}{2\pi(60)} \approx \mathbf{0.12223\ H/km}$$

$$B_{6-7}(S/km) = \frac{B_{pu}}{Z_{base}} = \frac{1.1730}{1600\ \Omega} \approx 7.3313 \times 10^{-4}\ S/km$$

$$C_{6-7}(F/km) = \frac{B_{6-7}}{2\pi f} = \frac{7.3313 \times 10^{-4}}{2\pi(60)} \approx \mathbf{1.94472 \times 10^{-6}\ (F/km)}$$

3. The lines between 9 - 10 is assumed to operate within the 33 kV section of the network.

$$Z_{base} = \frac{(V_{base})^2}{S_{base}} = \frac{(33 \times 10^3 \text{ V})^2}{100 \times 10^6 \text{ VA}} = \mathbf{10.89\ \Omega}$$

$$R_{9-10}(\Omega/\text{km}) = R_{\text{pu}} \cdot Z_{\text{base}} = 0.0010 \cdot 10.89\ \Omega = \mathbf{0.01089\ \Omega}/\text{km}$$

$$X_{9-10}(\Omega/\text{km}) = X_{\text{pu}} \cdot Z_{\text{base}} = 0.0030 \cdot 10.89\ \Omega = \mathbf{0.03267\ \Omega}/\text{km}$$

$$L_{9-10}(\text{H/km}) = \frac{X_{9-10}}{2\pi(60)} = \frac{0.03267}{376.99} \approx \mathbf{8.666 \times 10^{-5}}\ \text{H/km}$$

The summary of the calculated data for the transmission lines are in Table 4.

TABLE 4 – Lines parameters calculated

Line	V_{base}	Resistances Ω	Inductances H	Capacitances F
5 - 6	400 kV	0	0.016976	0
6 - 7	400 kV	2.4	0.12223	1.94472×10^{-6}
9 - 10	33 kV	0.01089	8.666×10^{-5}	0

6.4 Loads and shunt compensation

6.4.1 Loads

The loads at Buses 8 and 11 are modeled as constant P-Q loads to capture the worst-case scenario for voltage stability analysis. This ensures that the reactive power demand increases as the network voltage drops. The corrected values for the different load levels are summarized in Table 5.

TABLE 5 – Loads parameters

Bus	P (MW)	Q (MVAr)	
8	3271	1015	(load level 1)
	3320	1030	(load level 2)
	3345	1038	(load level 3)
11	3384	971	(load level 1)
	3435	985	(load level 2)
	3460	993	(load level 3)

6.4.2 Shunt compensation

Fixed capacitor banks are implemented using the Three-Phase Parallel RLC Load block.To model a pure capacitor, the active power (P) and inductive reactive power (Q_L) are set to zero, while the capacitive reactive power (Q_C) is set according to the bus requirements, as shown in Figure 14. Bus 7 has a shunt capacitor with a rating of 763 MVAr, Bus 8 has 600 MVAr, and Bus 9 has the highest reactive power rating at 1710 MVAr.

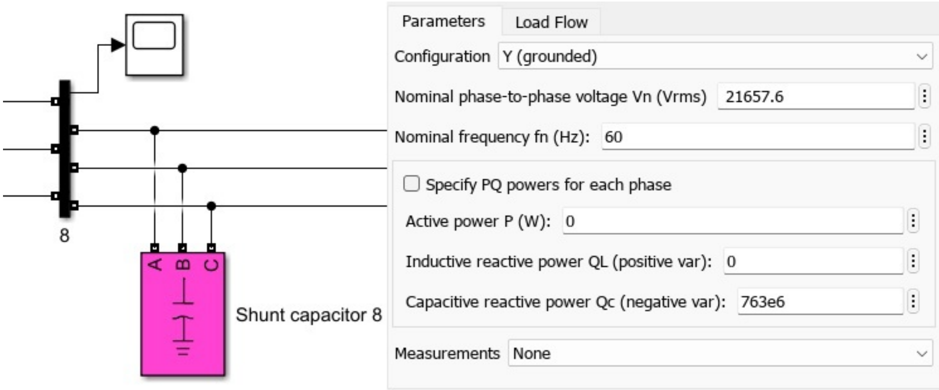

FIGURE 14 – Simscape - Shunt capacitors model

6.5 Final model

Figure 15 presents the complete system model. This model was built within the Simulink environment with specialized tools from the Simscape Electrical library. Crucially, every component as in Figure 6 and the components has been parameterized to operate under a consistent 100 MVA system base. All component impedances and admittances, initially given in per unit (pu), were converted to the necessary physical units (Ω/km, H/km, F/km) using the local base voltages established by the transformer ratios.

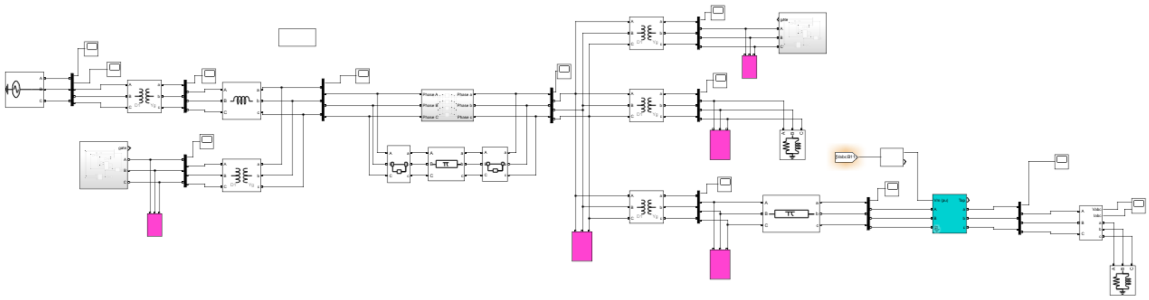

FIGURE 15 – Simscape - Complete system model

7 Simulation scenarios

7.1 Disturbance

An $N-1$ contingency, corresponding to the permanent loss of one of the five parallel lines between Bus 6 and Bus 7, is implemented in the main transmission corridor. This critical event increases the corridor's equivalent series reactance by 25%, leading to an instantaneous drop in voltage magnitudes. The implementation is shown in Fig 16 and details are as follows :

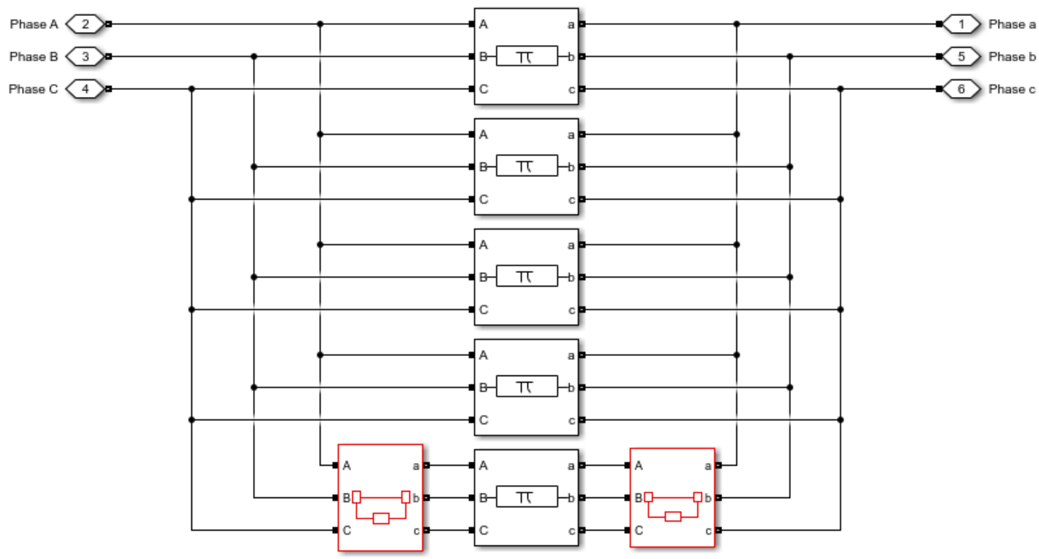

FIGURE 16 – Simulink implementation for disturbance generation.

— Parallel Line : Modeled with five parallel Three-Phase PI Section Line blocks.

— Switching Device : A Three-Phase Breaker block was placed in series with one of the lines to simulate the isolation of the circuit.

— Breaker Configuration : Initially closed to establish steady state, then programmed to open at $t = 10\,\mathrm{s}$ (after start-up transients decay), using high snubber parameters to ensure numerical convergence.

7.2 Scenario 1

This scenario evaluates the dynamic voltage stability to the previously defined disturbance for three progressively higher load levels (Table 5) following the line outage. The focus is on the interaction between the network's increased impedance, the action of the ULTC at transformer T6, and the reactive-power limits of generators G2 and G3.

For this scenario, the generation were considered as follows :

— G1 (Slack) : Voltage regulated at 0.9800 pu.

— G2 : 1736 MW with a voltage setpoint of 0.9646 pu.

— G3 : 1154 MW with a voltage setpoint of 1.0400 pu.

7.2.1 Load level 1 : Stable System Response

For this scenario, the load was set at 3271 MW and 1015 MVAr for Bus 8, and 3384 MW and 971 MVAr for Bus 11 and the ULTC transformer (T6) was considered with an initial tap ratio of 0.9750. The resultant time-domain responses are shown in Figure 17, which displays the voltages at Buses 7, 10, and 11, as well as the terminal voltage, field current, and reactive power output of Generator G3. The dynamic response of Generator G2 is presented separately in Figure 22.

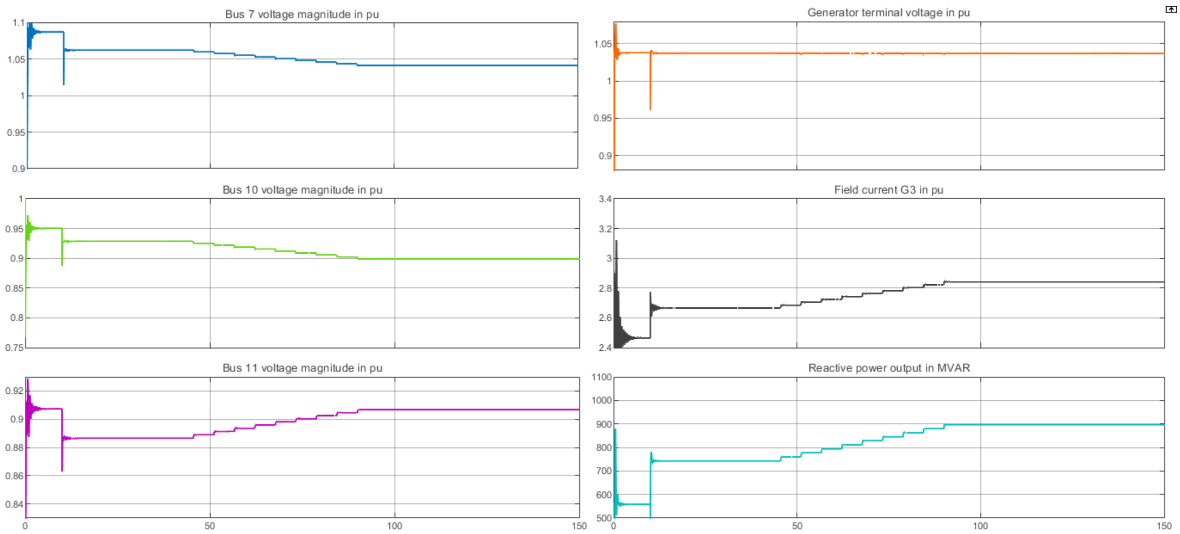

FIGURE 17 – Simulation outputs for Load Level 1.

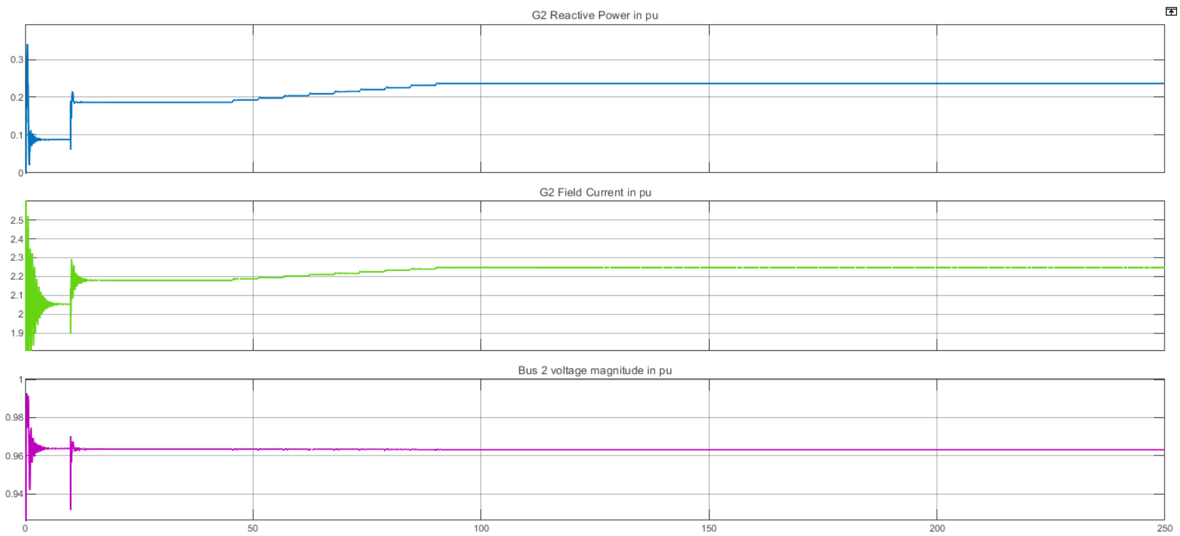

FIGURE 18 – Time responses for generator G2 for Load Level 1

The following observations characterize the system's response :

1. **Initial Impact :** The loss of the line immediately increases the network impedance, causing an instantaneous drop in the voltage magnitudes at both transmission and load levels.

2. **Secondary Control Response :** The ULTC on T6 detects the voltage deviation at Bus 11. It initiates tap movements 30 s after the disturbance and successfully restore the voltage to nearly its reference value within approximately 45 seconds after disturbance.
3. **Generators Stability :** Throughout the transient, the field current of generator G3 remains below its continuous thermal limit. Consequently, the Automatic Voltage Regulator (AVR) maintains full control over the terminal voltage. The reactive power output (Q) of Generators G3 and G2 increases immediately following the disturbance to compensate for the higher equivalent reactance.

Based on these results, the following technical conclusions are drawn :

— **Reactive Power Reserve :** The pre-disturbance loading at Bus 8 and Bus 11 is low enough that the system operates with a significant reactive power reserve. This enabled Generator G3 to increase its Q output to approximately 900 MVAr and Generator G2 to provide approximately 0.15 pu of additional support without reaching their capability curve limits.

— **Coordination with ULTC :** While the ULTC on transformer T6 works to restore the voltage at Bus 11, it inherently increases the reactive power demand on the source.

— **Steady-State Recovery :** Once the transient period ends (around $t = 90\,\mathrm{s}$), the Q output stabilizes at a new, higher equilibrium point. Because this value is within the continuous rating of the machine, the terminal voltage remains under the control of the Automatic Voltage Regulator (AVR).

— **Final Steady-State and Stability :** The system achieves a new stable equilibrium. The ULTC restores Bus 11 to near its nominal voltage, while uncontrolled Buses 7 and 10 settle at permanently reduced levels ($\approx 1.04pu$ and $\approx 0.90pu$, respectively). Generators G3 and G2 stabilize within their operational limits. With all critical variables at sustainable values, the system is confirmed voltage stable.

In general, the system demonstrated sufficient reactive power margins to absorb the specified contingency while maintaining voltage stability at the simulated load level. The coordinated response of generator AVRs and the transformer ULTC was effective and within operational constraints.

7.2.2 Load level 2

For this scenario, the load was set at 3320 MW and 1030 MVAr for Bus 8, and 3435 MW and 985 MVAr for Bus 11 and the ULTC transformer (T6) was considered with an initial tap ratio of 0.9938. The resultant time-domain responses are shown in Figure 21, which displays the voltages at Buses 7, 10, and 11, as well as the terminal voltage, field current, and reactive power output of Generator G3. The dynamic response of Generator G2 is presented separately in Figure 20.

The following observations characterize the system's response :

1. **Initial Impact :** Similar to Load Level 1, the loss of the line causes an immediate voltage drop across the entire network. However, due to the higher loading,

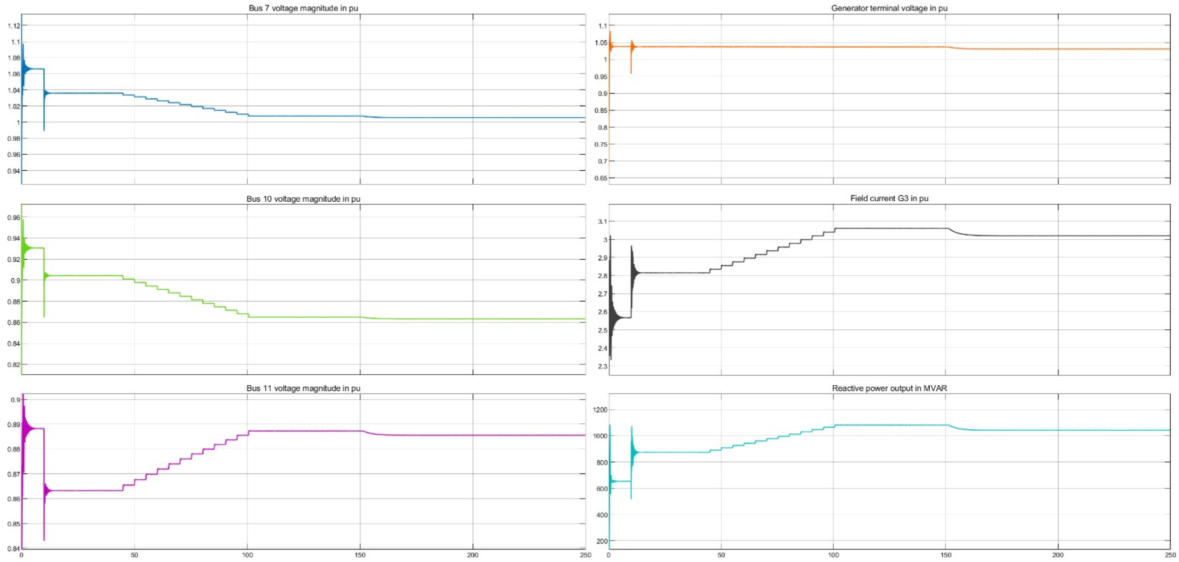

FIGURE 19 – Simulation outputs for Load Level 2.

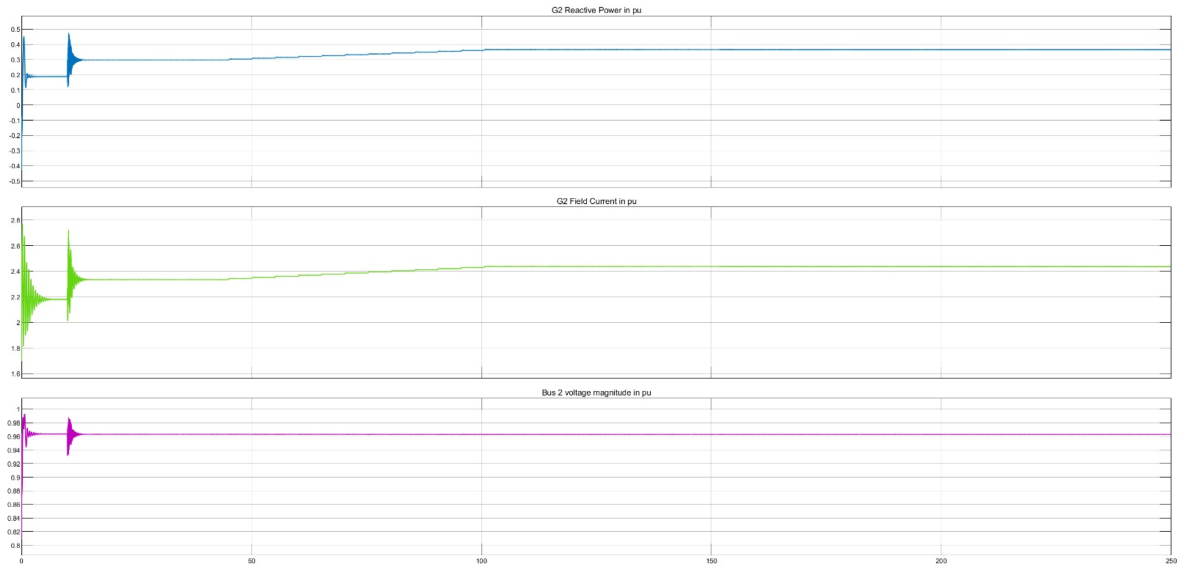

FIGURE 20 – Time responses for generator G2 for Load Level 2

the initial magnitudes are lower.

2. **Secondary Control Response :** The ULTC on transformer T6 detects the low voltage at Bus 11 and initiates tap movements in an attempt to restore voltage. This action, however, creates a voltage trade-off : as T6 draws more current to raise Bus 11 voltage, the reactive power (Q) demand increases further, placing additional stress on the already-stressed generators. The ULTC continues to operate until the generator's overexcitation limiter (OXL) activates, which signals that the system's reactive power reserve has been exhausted. At this point, the ULTC stops its corrective action, as further tap increases would be ineffective and could worsen system conditions. Consequently, Bus 11 voltage

stabilizes at a degraded equilibrium of approximately 0.89 pu (well below the nominal reference).

3. **Generators Stability :**
   - **G3 :** The generator responds to the increasing reactive power demand by raising its Q output to approximately 1100 MVAR. As a result, its field current i_{fd} climbs rapidly and exceeds its continuous thermal limit (around 3.02 pu).
     However, the response is not instantaneous. The generator holds at this maximum value for a defined period of time, allowing for short-term emergency reactive support. This intentional delay is a key feature of the Overexcitation Limiter (OXL), designed to prevent unnecessary activation during brief transients and to make use of the rotor's temporary overload capability.
     Once this preset time over, the OXL initiates its control action. It takes command of the excitation system, over the AVR, and begins ramping down the field current to return it to a safe level and protect the generator from thermal damage. This action causes the system voltages to lose voltage regulation and settle into a new, degraded equilibrium point.
   - **G2** also increases its reactive output and field current (settling near 2.3 pu) to support the transmission system, but it operates closer to its limits than in the previous case.

Based on these results, the following technical conclusions are drawn :
- **Reactive Power Reserve :** The high load levels exhausted the system's reactive power reserves. G3 reached its physical limit, as evidenced by its field current exceeding the continuous rating and activating the Overexcitation Limiter (OXL). This marked the exhaustion of the primary voltage support resource.
- **Coordination with ULTC :** The corrective action of the ULTC created a destabilizing feedback loop by increasing reactive power demand. This loop was terminated when the generator's OXL activated, proving that the reactive power supply limit, not the ULTC's tap range, was the binding constraint on voltage recovery.
- **Steady-State Recovery :** The system failed to return to its nominal voltage profile. The OXL's intervention and the subsequent loss of voltage regulation from G3 forced a degraded equilibrium with persistently low voltages.
- **Final Steady-State and Stability :** The system reached a steady state, confirming voltage stability for this load level, but at a fragile, heavily stressed equilibrium. Operating with exhausted reserves and low voltages, the system is now at the brink of collapse, highly vulnerable to any further increase in load or an additional contingency.

In general, this scenario highlights a critical voltage stability limit. The system's integrity relied entirely on the short-term overload capability of Generator G3. Once the timed protection of the OXL engaged and withdrew that emergency support, the system stabilized in a severely degraded state, vulnerable to any additional disturbance.

7.2.3 Load level 3

For this scenario, the load was set at 3345 MW and 1038 MVAr for Bus 8, and 3460 MW and 993 MVAr for Bus 11 and the ULTC transformer (T6) was considered with an initial tap ratio of 1. The resultant time-domain responses are shown in Figure **??**, which displays the voltages at Buses 7, 10, and 11, as well as the terminal voltage, field current, and reactive power output of Generator G3. The dynamic response of Generator G2 is presented separately in Figure **??**.

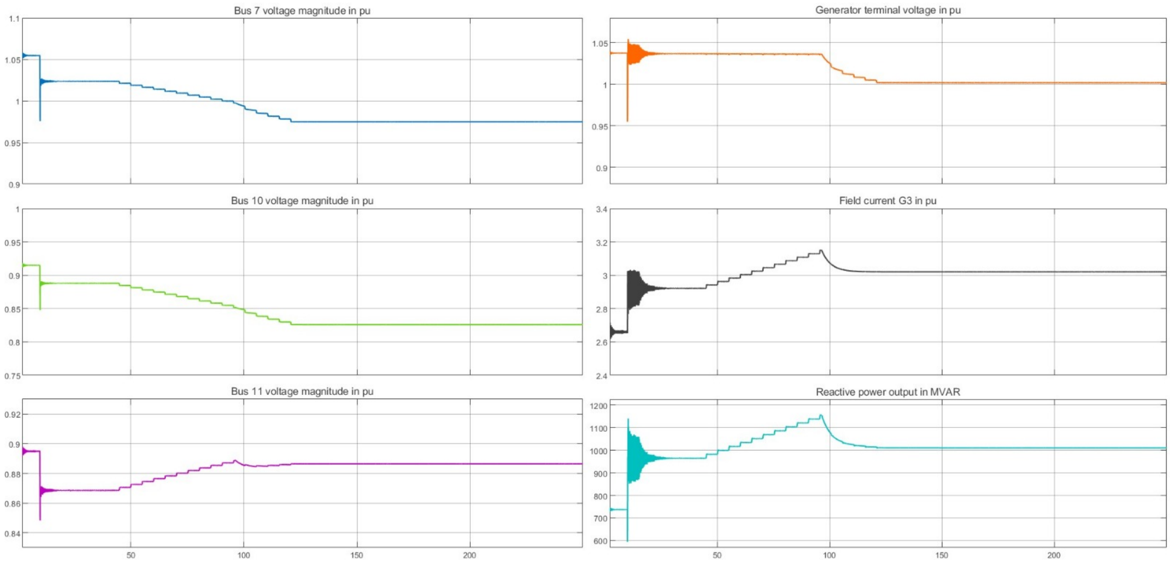

FIGURE 21 – Simulation outputs for Load Level 3.

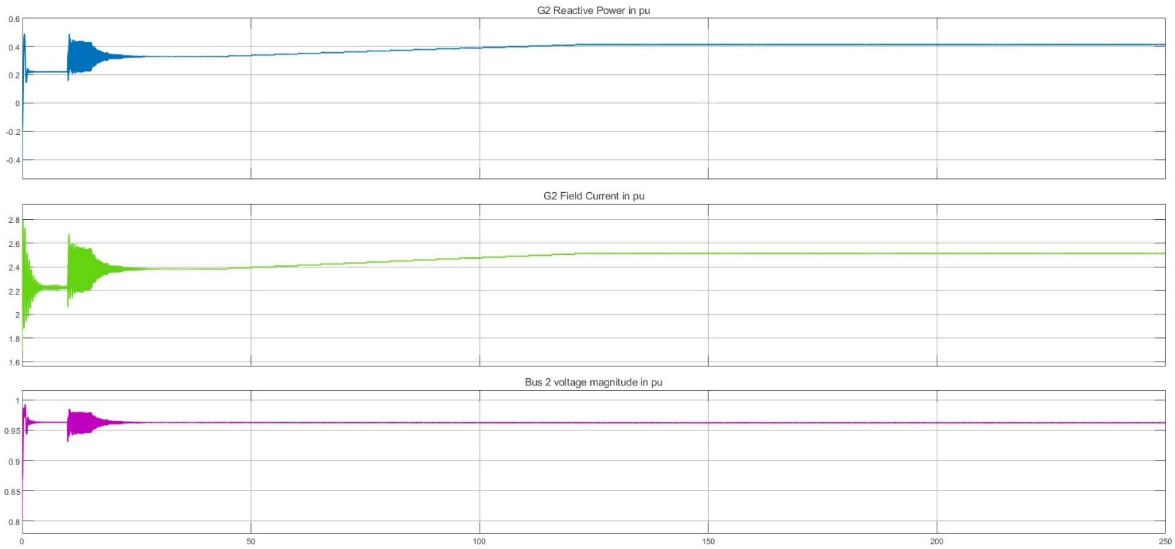

FIGURE 22 – Time responses for generator G2 for Load Level 3

The following observations characterize the system's response :

1. **Initial Impact :** Similar to the previous cases, the voltage drop and due to the higher loading, the initial magnitudes are lower.
2. **Secondary Control Response :** The ULTC initiates its standard corrective action, increases the load seen by the transmission network, drawing more reactive power and causing a further drop in voltages.
3. **Generators Stability :** The reactive power output and field current rise and quickly exceeds its maximum allowable limit. The Overexcitation Limiter (OXL) activates, and the generator loses its ability to regulate voltage. This removes the primary source of dynamic reactive support from the system.

Based on these results, the following technical conclusions are drawn :
- **Reactive Power Reserve :** The system's dynamic reactive power reserve (Generator G3) was the first resource to be completely exhausted, occurring well before the ULTC finished its action.
- **Coordination with ULTC :** Under these extreme conditions, the ULTC's restorative action became actively destabilizing. By increasing the load demand in an attempt to raise the low voltage, it created a runaway positive feedback loop that accelerated the collapse instead of halting it.
- **Steady-State Recovery :** A steady state was achieved, but only after all available controls were exhausted. Recovery to nominal voltage was impossible ; the final state represents the best possible outcome given the exhausted resources.
- **Final Steady-State and Stability :** The system is voltage stable for this specific load level, as it reaches a steady equilibrium. However, it exists in a critically degraded state with no control margin. The stability is entirely fragile, sustained only because both the generator's OXL and the transformer's tap changer have reached their hard limits.

In this case, the system operates at the absolute boundary of secure operation. The sequence of events—first generator limit, then ULTC limit—highlights the layered defense of power system controls. While stable, the system has zero resilience ; any further increase in load or an additional contingency would lead directly to collapse.

7.3 Scenario 2 - Case Study : Load Effect and Voltage Stability

7.3.1 Objective :Load Modeling and Transformer Configurations

The load at bus 11 is modelled as 50% constant impedance and 50% constant current for both active and reactive components ; the action of the ULTC transformer (T6) supplying this load is modelled in detail. The load at bus 8 is modelled as constant MVA for both active and reactive components. The transformer T4 supplying this load is assumed to have a fixed tap.

The Scenario

The study compares two different types of electrical loads at **Bus 8** :
- **Previous Study :** The load was assumed to be constant MVA for both active and reactive parts.

— **Current Study :** The load at Bus 8 is replaced by an induction motor.

The Mechanism of Voltage Collapse

When a system experiences a voltage drop, induction motors behave differently than static loads. This leads to a more severe impact on the grid :

— **Reactive Power Surge :** As the system voltage drops, the induction motor draws more current and significantly more reactive power (measured in MVAr) to maintain its torque.

— **Stalling :** At approximately 65 seconds, the motor can no longer maintain its speed and stalls.

— **System Failure :**

  — **Active Power (MW) :** Drops sharply when the motor stalls.

  — **Reactive Power (MVAr) :** Spikes rapidly as the motor tries to recover, which puts immense stress on the grid.

  — **Voltage Collapse :** This massive demand for reactive power causes the bus voltage to plummet, leading to a total voltage collapse if not compensated.

Comparison : Constant MVA vs. Induction Motor

The graphs highlight a critical difference in system resilience :

— **With Constant MVA Load :** The voltage stays relatively stable and manageable over time.

— **With Induction Motor Load :** The voltage remains stable until the 65-second mark, at which point it drops vertically toward zero.

Technical Parameters of the Motor

The motor used in this simulation is a heavy industrial unit with the following specifications :

— **Rating :** 3600 MVA, 60 Hz.

— **Load Torque Exponent (m) :** 2.0 (meaning torque is proportional to the square of the speed, $T_L = T_0\omega_r^2$).

— **Inertia Constant (H) :** 0.6 s.

7.3.2 Results

This case differs from the above in that the active power component of load at bus 8 is represented as an induction motor. Only load level 2 is considered. The motor stalls at about 65 seconds. This results in a decrease in active power absorbed by the motor. However, the reactive power drawn by the motor increases rapidly. This causes voltage collapse. For comparison, the voltage response with constant MVA load at bus 8, as computed in (a), is also shown

FIGURE 23 – Motor Speed

FIGURE 24 – Reactive Power Absorbed By the Motor

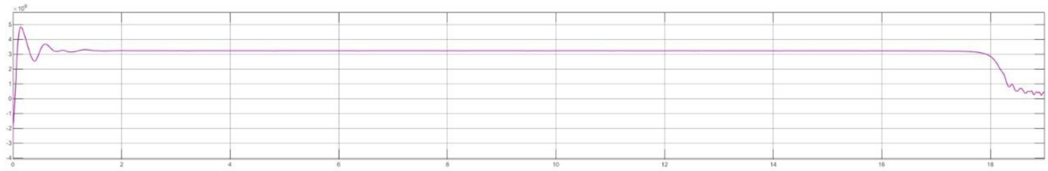

FIGURE 25 – Active Power Absorbed By the Motor

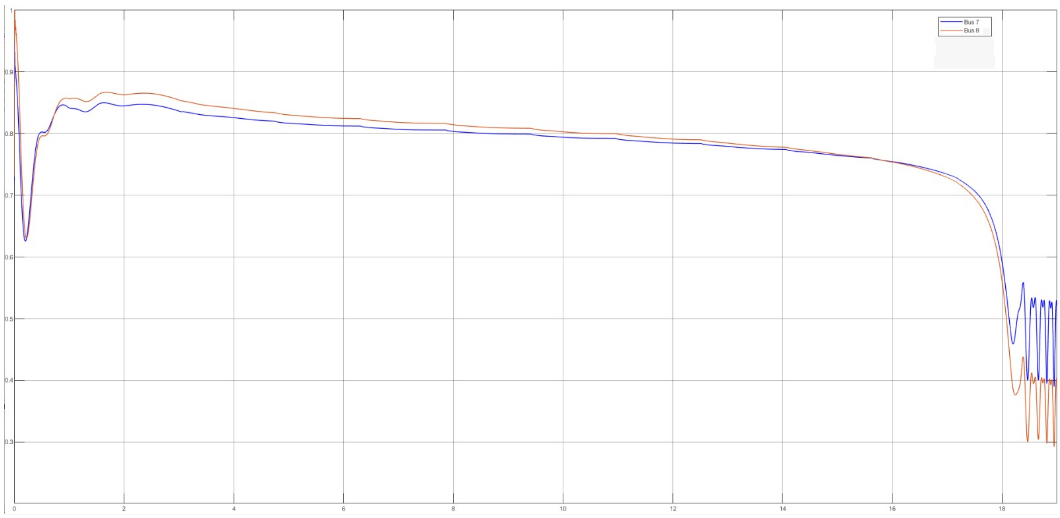

FIGURE 26 – Voltage magnitude at bus 7 and bus 8 with induction motor load at bus 8 ; system at load level 2

8 Conclusion

8.1 Scenario 1 :Conclusion

The dynamic voltage stability analysis conducted for Scenario 1 evaluates the system's resilience to an $N-1$ contingency under three progressively higher load levels. The simulation results illustrate the critical transition from a robust, stable system to one operating at the threshold of voltage collapse.

8.1.1 Key Technical Findings

- **Impact of Network Impedance :** The loss of one of the five parallel lines between Bus 6 and Bus 7 increased the corridor's equivalent series reactance by 25%. This structural change caused an immediate drop in voltage magnitudes and significantly increased the reactive power (Q) losses within the transmission path.
- **Reactive Power Reserve Dynamics :**
  - At **Load Level 1**, the system possessed sufficient reactive power reserves. Generators G2 and G3 responded to the disturbance without exceeding their continuous thermal ratings, allowing the Automatic Voltage Regulator (AVR) to maintain terminal voltage control.
  - At **Load Level 2 and 3**, the increased loading exhausted the available reserves. The activation of the **Overexcitation Limiter (OXL)** on Generator G3 proved to be the decisive factor in system stability, as it forced the generator to reduce its field current to protect the rotor, thereby losing the ability to regulate voltage.
- **ULTC and Load Interaction :** The Under-Load Tap Changer (ULTC) at transformer T6 attempted to restore the voltage at Bus 11. While effective at low loads, at higher load levels, the ULTC action created a destabilizing feedback loop. By raising the secondary voltage, it increased the reactive current demand on the already stressed generators, accelerating the onset of the OXL intervention.

8.1.2 Final Stability Assessment

Table 6 – Voltage Stress Summary for Scenario 1 Load Levels

Load Level	**Stress Status**	**Limiting Factor**
Level 1 (3271 MW)	Less stressed	None (Sufficient Reserves)
Level 2 (3320 MW)	Stressed	OXL Activation / Degraded Equilibrium
Level 3 (Higher)	More Stressed	Exhaustion of Short-term Overload

Final Conclusion : The system is confirmed to be **voltage stable** for the $N-1$ contingency at Load Level 1. However, as the load increases toward Levels 2 and 3, the system reaches its **Physical Reactive Power Limit**. The transition from AVR-controlled operation to OXL-limited operation results in a fragile steady state with significantly reduced voltage profiles. These results demonstrate that the system's ability to withstand contingencies is strictly dependent on maintaining a sufficient reactive power margin to prevent the activation of overexcitation limiters.

8.2 Scenario 2 :Conclusion

The comparative analysis of Bus 8 reveals that **load modeling is a decisive factor** in predicting voltage stability and system collapse. While the constant MVA model provides a relatively stable baseline, it fails to capture the high-risk dynamic transients associated with heavy industrial induction motors.

Key Findings

— **Dynamic Instability :** The study demonstrates that static load models (Constant MVA) tend to overestimate system resilience. Under identical stress conditions, the constant MVA load remained stable, whereas the induction motor load led to a **total voltage collapse**.

— **The Stalling Phenomenon :** At approximately $t = 65$ seconds, the motor reaches a critical slip where electromagnetic torque can no longer support the mechanical load ($T_L = T_0\omega_r^2$). This results in the motor stalling.

— **Reactive Power Surge :** Post-stalling, the motor acts as a massive reactive sink. The rapid spike in MVAr demand exceeds the transmission system's delivery capability, creating a positive feedback loop that causes the bus voltage to drop vertically toward zero.

Comparison Summary

The following table summarizes the divergent behaviors observed in the simulation :

Feature	Constant MVA Load	Induction Motor Load
Stability Trend	Predictable and manageable	Non-linear and volatile
Post-65s Behavior	System maintains equilibrium	Sudden stall and voltage collapse
Reactive Demand	Stays constant/linear	Exponential increase at stall point
System Risk	Low (Over-optimistic)	High (Sudden catastrophic failure)

TABLE 7 – Comparison of Stability Performance at Bus 8

Engineering Implications

For power system reliability, this case highlights that operating margins must be calculated based on the *stalling point* of dynamic loads rather than simple thermal limits. Protection schemes, such as Under-Voltage Load Shedding (UVLS), must be designed to intervene before the 65-second threshold to prevent irreversible collapse.