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Research Article

Case Study on Energy Reliability Applications and Mathematical Models in The Distribution Network

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ABSTRACT

This study focuses on the reliability of power systems, examining it from technical, economic, and decision-making perspectives. Reliability is a crucial concept in assessing the ability of an energy system to operate smoothly and provide uninterrupted energy supply. First and foremost, it is pointed out that the majority of failures in power systems occur in distribution systems. This involves examining how customers might react to energy interruptions and the economic consequences of those reactions. At the component level, degradation models have been introduced to scrutinize reliability in greater detail. These models elucidate how components may degrade during system operation and how this degradation affects reliability. In conclusion, this study underscores the significance of integrating new technologies and renewable energy sources into energy systems. Additionally, it asserts that reliability and energy sustainability are two fundamental pillars for societal progress. As a result, the reliability and sustainability of energy systems hold critical importance in meeting the energy needs of societies and shaping the future of the energy sector.

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1. INTRODUCTION

Energy planning is the process of developing long-term policies with the aim of guiding the future of the local, regional, or even global energy system. Globalization, rapid population growth, and the industrialization efforts of countries have led to a significant increase in the demand for energy and natural resources. The International Energy Agency predicts that the world's primary energy demand will increase by 40% between 2020 and 2030. This translates to an annual average demand growth rate of approximately 1.5%. Research indicates that this trend will take the world's primary energy demand from 12 billion Tons of Equivalent Petroleum in 2020 to 16.8 billion TEP by 2030.

Energy production sources are classified into primary energy sources and renewable energy sources. In primary energy sources, hydropower is related to water energy, thermal energy is associated with coal, oil, and gas, and nuclear energy refers to nuclear power. Renewable energy sources can also be considered as alternative energy sources and are exemplified as follows: wind, solar, geothermal, hydroelectric, biomass, wave power, and solar panels. It's important to note that alternative energy sources cannot fully replace primary energy sources. This is because alternative energy sources may fail to fulfill one of the most critical criteria of primary energy sources, which is "continuity."

Power system reliability primarily focuses on addressing issues related to service interruptions and energy loss. It is often defined as a target, particularly considering indicators that are directly relevant to customers. Typical reliability indicators for energy service providers include SAIFI, SAIDI, and CAIDI. Over time, these indicators have become standardized measures for assessing the reliability of electrical systems and are widely used in many publications. Recent studies conducted by [1] have identified reliability sub-criteria within decision-making features and presented an optimal model for a smart grid. These studies have gained popularity through applications in the field of power system reliability [2, 3]. One commonly used technique to optimize and manage power system reliability is reliability-centered maintenance (RCM). In many publications, it has been emphasized that in many cases involving multi-component systems, maintenance operations can either occur too early and have no impact on the system or occur too late and require corrective maintenance. This also addresses the provision of differentiated reliability services to customers with different reliability requirements. Recent publications have highlighted the importance of integrating reliability characteristics for maintenance operations, especially in scenarios involving deteriorating systems and components [4].

In addition, there is a need to improve the existing grid infrastructure and establish new transmission line facilities to reliably meet the increasing demand for electrical energy.

Electricity transmission systems typically form the backbone of interconnected power systems and operate at high voltage levels [5, 6]. The planning of electricity transmission systems aims to ensure grid security at the minimum cost. This planning includes long-term, medium-term, and short-term technical and economic grid analyses based on the growing demand [7]. Commonly, analysis tools such as load flow analysis, short circuit analysis, harmonic and flicker analysis, dynamic analysis, grounding, and protection coordination analysis are used to determine the operating conditions of transmission facilities [8]. Simulation studies have been employed in the literature to examine the impact of power electronics-based Flexible AC Transmission System (FACTS) devices such as STATCOM and SVC on voltage stability [9]. The effect of phase-shifting transformers on static voltage stability and the usability of On-Load Tap Changers (OLTC) transformers for voltage control have been evaluated [10, 11]. Voltage variations at busbars before and after the commissioning of series capacitors on a transmission line have been analyzed [12].

Voltage collapse issues in power systems have been analyzed using multi-layer sensor-based artificial neural networks [13]. Methods used to compensate for voltage disturbances in power systems have been explained. The effects of wind and solar power plants on voltage stability in the power system have been studied [14, 15]. Voltage collapse problems have been compared under different scenarios using Matlab and DigSilent programs [16].

In this study, the impact of changes in active power and reactive power, transmission line lengths, and series capacitor applications on voltage stability in the power system have been examined. Effective comparisons have been made based on the modeling of actual grid parameters in the DigSilent program.

2. ELECTRICAL POWER SYSTEM RELIABILITY ASSESSMENT AND INDICES

The reliability of electrical power systems is of vital importance in ensuring uninterrupted electricity supply to end-users. Reliability assessment helps identify potential risks and failures that can affect the overall performance of the system. It involves evaluating various components of the power system, including generators, transmission lines, transformers, and distribution networks. One of the primary reasons for conducting reliability assessment is to ensure that the system can withstand unexpected events such as natural disasters, equipment failures, or human errors. Engineers can identify weak points by assessing the system's reliability and develop strategies to mitigate them before they lead to significant disruptions. Various methods, including probabilistic and deterministic approaches, can be used to assess the reliability of electrical power systems. Probability-based methods take into account various factors, including weather models, human behavior, and equipment failures, while deterministic methods rely on specific rules and regulations. In conclusion, reliability assessment is critical to ensuring the smooth operation of electrical power systems. By identifying potential risks and developing measures to mitigate them, it helps provide continuous and reliable power supply to end-users [17].

Reliability in power systems is a crucial aspect, particularly concerning the uninterrupted supply of electricity to end consumers. Reliability indices are used to evaluate the performance and effectiveness of power systems in achieving this goal. In this article, we will explore the world of reliability indices in power systems. One of the most important reliability indices is the System Average Interruption Duration Index (SAIDI). This index measures the average duration of electricity interruptions per customer in a year. Another significant index is the System Average Interruption Frequency Index (SAIFI), which determines the frequency of electricity interruptions per customer in a year. Other noteworthy indices include the Momentary Average Interruption Frequency Index (MAIFI), which measures the number of momentary interruptions in power supply per customer, and the Customer Average Interruption Duration Index (CAIDI), which determines the average time for electricity to be restored after an interruption.

Reliability indices are critical for power services because they help identify problematic areas and work towards improving their performance. By monitoring and enhancing these indices, electricity distribution companies can provide more reliable and uninterrupted power supply to their customers. In conclusion, power system reliability is of utmost importance, and reliability indices are just one of the many ways in which energy organizations measure their performance and strive for better reliability [18].

2.1. Modeling Techniques for Power System Reliability Analysis

Reliability analysis of power systems is crucial to ensure continuous electricity supply to consumers. One of the most effective methods for analyzing power system reliability is through modeling techniques. These techniques enable engineers to simulate various scenarios and identify potential issues that can impact system reliability. One commonly used modeling technique is Monte Carlo simulation. This approach involves randomly selecting values for various parameters within the model, such as failure rates and repair times, and running the simulation thousands of times to determine the probability of different outcomes. Another technique is the Markov model, which uses a series of states and transitions to represent the system's behavior over time. Using data that reflects real-world conditions is essential to obtaining accurate results. This includes historical data on equipment failures, weather patterns, and other relevant variables. Additionally, considering the impact of external factors like natural disasters and human error is crucial.

Engineers can gain a better understanding of the system's behavior and identify potential areas for improvement by using modeling techniques for power system reliability analysis. With this information, electricity distribution companies can make informed decisions about maintenance programs, system upgrades, and other measures to increase reliability and reduce downtime.

In conclusion, power system reliability is highly important, and modeling techniques are valuable tools for assessing and improving reliability [19].

2.2. Maintenance Strategies to Improve Power System Reliability

Power systems are integral to any industrial or residential operation, and like all machinery, they require regular maintenance to ensure their reliability and efficiency. In this article, we will discuss some of the best maintenance strategies that can help improve power system reliability. First and foremost, regular inspections and checks should be conducted to identify potential issues before they become serious problems. This includes monitoring voltage levels, assessing the condition of cables, and checking for signs of wear or damage. Secondly, implementing a preventive maintenance program can help minimize downtime and prevent unexpected power interruptions. This program may include tasks such as cleaning, lubrication, and tightening loose connections. Investing in modern technologies like sensors and remote monitoring systems is another strategy that can help detect potential problems before they escalate. Lastly, training employees in proper handling and maintenance procedures can reduce the risk of human error and contribute to the long-term reliability of the power system. In conclusion, prioritizing regular maintenance using these strategies can lead to enhanced power system reliability, reduced downtime, and increased productivity. Ensuring the optimal performance of the system is crucial for overall operations, making regular maintenance a top priority [20].

2.3. Mathematical Modeling in Transmission and Distribution Systems

In power systems, the fundamental objective is to efficiently deliver electrical energy from generation sources to consumption points. This electrical transmission is typically accomplished through high-voltage transmission lines, which play a critical role in the process. The equivalent circuit illustrated in Figure 1 serves as a mathematical representation of a transmission line, a vital component of power systems [21]. This circuit comprises various elements:

- VS (Voltage Source): This represents the voltage supplied to the transmission line, usually originating from power plants or distribution centers.
- R (Resistance): It signifies the resistance of the transmission line, which can lead to energy losses, particularly over longer distances.
- XL (Inductive Reactance): This component depicts the inductive reactance in the transmission line, representing its interaction with inductive loads.
- XC (Capacitive Reactance): XC represents the capacitive reactance in the transmission line, symbolizing its interaction with capacitive loads.
- VR (Receiver Voltage): VR denotes the voltage at the receiver end of the transmission line.

The relationships between these components are expressed mathematically as follows:

- Total Impedance (Z) Relationship: $Z = R + jX$ (Here, 'j' represents the complex unit.)
- Active Power (P) Relationship: $P = {|VR|^2}/{R} - {|VS|^2}/{R}$
- Reactive Power (Q) Relationship: $Q = {|VR|^2}/{X} - {|VS|^2}/{X}$
- Phase Angle (δ) Relationship: $\delta = \tan((|VR| \sin \delta - |VS| \sin 0)/(|VR| \cos \delta - |VS| \cos 0))$

These equations mathematically describe the behavior of transmission lines during the transmission of electrical energy. These mathematical models are used in the analysis, design, and operation of power systems. Electrical engineers employ these models to optimize the performance of power systems and ensure the efficient transmission of electrical power [22].

3. MATERIAL AND METHOD

In power systems, the primary purpose of transmission lines is to deliver the generated electricity to consumers. The equivalent circuit of an electrical transmission line between two buses is depicted in Figure 1 [23, 24]. In this configuration, it represents VS as the source voltage, R as resistance, XL as inductive reactance, XC as capacitive reactance, and VR as the receiver voltage. The impedance and active-reactive power relationships associated with this electrical transmission line are provided in Equations. In these equations, Z represents the total impedance, P represents active power, Q represents reactive power, and δ represents the phase angle between the source and receiver voltages.

Expanding the existing distribution network is a comprehensive problem that involves making strategic decisions such as whether to add new lines, whether existing lines need to be upgraded, whether new transformers are needed, where to install new transformers, what capacity the transformers should have, whether old transformers need strengthening, where to install various types of distributed generation sources, and how much electricity from which sources should be supplied to specific consumption points. Distribution Network Expansion Problem (DNEP) is a complex problem, especially in a NP-Hard structure, and integrating distributed generation further complicates the problem [25]. Therefore, developing efficient mathematical models is crucial to achieve the best (optimal) results in a shorter time.

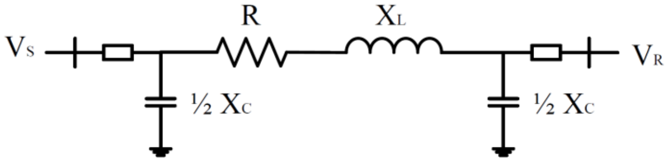

Figure 1. Equivalent circuit of an electrical transmission line between two busbars

The most commonly used network structure in distribution networks is the radial network [26]. An example of a radial network structure is provided in Figure 2. Radial networks, also known as branched networks, have a tree-like structure and do not allow closed loops. In this type of network, customers receive energy from a single distribution center and line. The radial network structure is often preferred because it is cost-effective and simple.

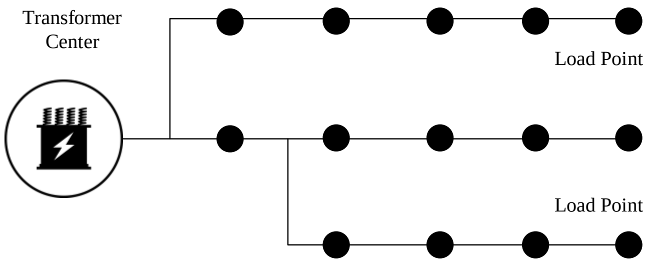

Figure 2. Radial network example as a Distribution Network Model

The choice of conductor material, length, and topology of transmission lines used in the construction of transmission lines can significantly impact the power system. Their reactive power characteristics, XC for capacitance, and XL for inductance, depend on the design. When a transmission line is loaded below its normal rating, it behaves capacitive, while when loaded above its normal rating, it behaves inductively. Using the equations, it is possible to determine the direction and magnitude of active-reactive power flow between two buses. The length and structure of the transmission line affect its capacity to carry both active and reactive power. Furthermore, changes in the quantity of active and reactive power can lead to variations in voltage levels and phase angles at the buses. In order to establish a radial structure, there should be one input for each demand node, and for demand nodes with no requests (if any), there should be at most one input. Constraints for this situation can be formulated as follows eq. 1 and eq. 2 [27].

$$\sum_{l\in L}\sum_{i\in\Omega}\sum_{k\epsilon K} y_{ijkt}^{t} = 1 \forall j \in \Omega, \forall t \in T \quad (1)$$

$$\sum_{l\in L}\sum_{i\in\Omega}\sum_{k\epsilon K} y_{ijkt}^{t} \leq 1 \forall j \in \Omega, \forall t \in T \quad (2)$$

When these constraints are considered alongside the network flow constraint, they are sufficient to establish a classic radial configuration. Due to the flow constraint, nodes require energy input, and consequently, they will connect to the single energy point, which is the transformer center. However, these constraints alone are not sufficient to ensure radially. When distributed generation sources are installed, nodes can create a disconnected loop in the network to receive energy from that source, and the connection to the transformer center may not occur. An example of a network that could result when the above constraints are applied is provided in the diagram. In this diagram, the Distributed Generation at each node is providing energy to the node. The input constraints for each node have been met, and a disconnected network segment has formed, not connecting to the transformer center. The distribution network can be expressed as a rooted tree with the transformer center considered as the root node [28]. When there are multiple transformer centers, it forms a forest structure. The formulation for the generalization of the Steiner tree problem is provided in constraints numbered in eq. 3-6 [29]. The network, denoted as G, is composed of the set of nodes V and edges E (G(V, E)). In the network, r represents the root node, and j represents the other nodes ($j \in V\{r\}$).

$$S_j = \begin{Bmatrix} 1, if\ j\ point\ on\ tree \\ 0, dd \end{Bmatrix}\ and\ S_r = 1\ or\ S_i \in \{0,1\} \quad (3)$$

$$X_e = \begin{Bmatrix} 1, if\ e\ line\ on\ tree \\ 0, dd \end{Bmatrix}\ and\ X_e \in \{0,1\} \quad (4)$$

$$\sum_{e\epsilon E(U)} X_e \leq \sum_{i\in\frac{U}{k}} S_i\ for\ all\ U \in V\ and\ k \in U \quad (5)$$

In our problem, since there is no potential for all nodes in the network to be interconnected, the set $E(U)$ can be selected from the lines that can form sub cycles. This is because we have prior knowledge of the existing and potential lines in the network we are interested in. Therefore, unnecessary calculations for lines that can never occur are avoided. Accurately determining the set $E(U)$ is crucial for reaching the correct result quickly. Taking into account certain characteristics of the problem and the model will greatly facilitate the determination of the set $E(U)$.

3.1. Key Factors Affecting Reliability of Power Systems: The Role of Transmission Lines and Network Design

In power systems, the primary purpose of transmission lines is to deliver generated electricity to consumers. The equivalent circuit of transmission lines is represented by the source voltage (VS), resistance (R), inductive reactance (XL), capacitive reactance (XC), and receiver voltage (VR). The total impedance (Z) of transmission lines and the relationships between active and reactive power are critical factors influencing the reliability of the system.

The Distribution Network Expansion Problem (DNEP) involves strategic decisions such as adding new lines, upgrading existing lines, and installing new transformers. The integration of distributed generation complicates this problem further. Developing effective mathematical models is crucial for achieving optimal results in a shorter time frame.

The most common structure in distribution networks is the radial network, which does not allow closed loops. In these networks, customers receive energy from a single distribution center. The radial structure is preferred due to its cost-effectiveness and simplicity.

The choice of materials, length, and topology of transmission lines significantly impacts the performance of the power system. When loaded below their normal rating, transmission lines exhibit capacitive behavior, while they behave inductively when loaded above their normal rating. Determining active and reactive power flows is essential for understanding variations in voltage levels and phase angles.

Two scenario studies investigate the effects of increases in active and reactive power consumption on network voltages:

Increase in Active Power Consumption: An increase in active power consumption negatively affects the voltage profile of the entire system.

Increase in Reactive Power Consumption: An increase in reactive power consumption has a more pronounced effect on the system's voltage stability, leading to lower voltage levels.

These studies provide valuable data for implementing necessary measures to enhance the reliability of the power system. In particular, the management of reactive power and the optimization of network structure are critical for improving the overall stability of the system.

3.2. Transmission Network Model: Single-Line Diagram

In this section, a portion of the existing electrical transmission system is discussed. The operating voltage in the created power system ranges from 380 kV to 34.5 kV. External grid connections at 380 kV are defined as external networks in the modeled system [30]. The power system consists of 5 buses, 3 transformers, and 2 transmission lines. The single-line diagram created in the DigSilent program is shown in Figure 3. The physical structure of the electrical transmission lines is overhead, and the cross-sectional areas of the conductors used may vary. Power system and model the transmission and distribution networks within this system using the DigSilent program. Please note that the specifics of the transmission lines, transformers, and buses in the system can vary significantly based on the actual configuration and requirements of the power system being modeled.

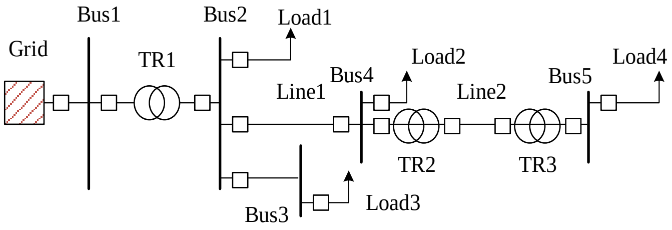

Figure 3. Single line diagram of the network modeled in the DigSilent program

In this section, simulation results using the DigSilent program are examined for several factors affecting voltage stability in a power system. Initially, the normal state of the network was determined. Subsequently, different scenario studies were configured by making changes to the network while considering the normal network state. Scenario Study-1 investigated the impact of an increase in active power consumption on bus voltages, while Scenario Study-2 examined the effect of an increase in reactive power consumption on the bus voltages on the consumer side.

3.3. Case Study-1: Increase in Active Power Consumption

In the normal network state, Bus 6 operates at 34.5 kV voltage level with a 10 MW load. To determine the effect of only the active power, the active power of Load 4 was increased while keeping the reactive power constant. Table 1 illustrates the changes in bus voltages in per-unit values corresponding to the increased active power values. Figure 3 shows the active power-voltage curve. It is observed that an increase in active power consumption leads to a decrease in bus voltages. An increase in active power consumption at a single point in the power system alters the voltage profile of the entire system. Specifically, the bus where consumption has increased is more affected. Table 1 presents the loading capacities of the lines resulting from the increase in active power, and Figure 4 shows the variation curves. For example, when the active power is 50 MW, the loading capacity of Line 2 has increased by approximately 7%. An increase in active power consumption has increased the loading capacities of the lines. Additionally, calculations were made based on simulation results for active powers of 10 MW and 50 MW. The results reveal the transmitted active power between Bus 4 and Bus 5, along with the loading capacity of Line 2.

TABLE I. Active power, voltage and line loading values in Case Study-1

Component / Capacity	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Line 1	Line 2
10 MW	1,000	0,996	0,995	0,99	0,98	7,87	32,5
20 MW	1,000	0,995	0,994	0,98	0,98	8,09	35,7
30 MW	1,000	0,995	0,994	0,98	0,98	8,32	39,0
40 MW	1,000	0,994	0,993	0,98	0,98	8,55	42,5
50 MW	1,000	0,993	0,992	0,98	0,97	8,81	46,2

For the case where the active power is 10 MW, the P value is obtained as 10.1MW, while the Loading ratio value is obtained as 10.34 MVA. On the other hand, for the case where the active power is 50 MW, the P value is obtained as 50.4MW, while the loading rate is obtained as 33.45%.

3.4. Case Study-2: Increase in Reactive Power Consumption

In this study, the reactive power consumption at Bus 6 has been increased, and the changes in bus voltages have been examined. Only the effect of reactive power has been considered to determine, assuming active power is constant. Table 2 shows the bus voltages for increasing reactive power values. Figure 5 depicts the reactive power-voltage curve. It is observed that the increase in reactive power consumption leads to a decrease in bus voltages. Especially, the voltage of the bus with higher reactive power consumption is more affected. In Case Study 2, the voltage levels are lower. For example, when the active power at Bus 6 is 50 MW, the bus voltage is 0.89 pu, whereas it drops to 0.65 pu when the active power is 50 MVAr. Therefore, the change in reactive power has a greater impact on the system's voltage stability. Additionally, calculations have been made based on simulation results for the cases where reactive power is 10 MVAr and 50 MVAr. When we examine the transfer of reactive power between Bus 5 and Bus 6, it is seen that the transmitted reactive power values exceed the desired reactive power value. The reason for this is that the increase in reactive power component increases the capacitive reactance losses on the transmission line. For the case of 10 MVAr of reactive power, the Q value is obtained as 14.3 MVar. For the case of 50 MVAr of reactive power, the Q value is obtained as 79.7 MVar.

TABLE II. Active power, voltage and line loading values in Case Study-1

Component / Capacity	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
10 MVAr	1,000	0,99	0,99	0,98	0,98
20 MVAr	1,000	0,99	0,99	0,98	0,97
30 MVAr	1,000	0,99	0,99	0,98	0,96
40 MVAr	1,000	0,99	0,98	0,97	0,95
50 MVAr	1,000	0,98	0,98	0,97	0,94

The increase in active power leads to a decrease in voltage levels at Bus 6. This drop poses a threat to system reliability, as low voltage levels can adversely affect the operation of electrical equipment and lead to failures. A reliable system must maintain specific voltage ranges.

When the active power reaches 50 MW, the loading capacity of Line 2 increases by 7%. While this indicates an increase in the system's carrying capacity, it must be monitored carefully to avoid overloading. Otherwise, excessive loading can weaken the reliability of the lines and increase the risk of outages.

An increase in reactive power consumption results in a further decline in bus voltages. The drop in voltage at Bus 6 from 0.89 pu to 0.65 pu indicates a disruption in the reactive power balance. Effective reactive power management is critical for voltage stability; poor management can threaten system reliability.

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The increase in reactive power transfer raises capacitive reactance losses in transmission lines and leads to exceeding desired values. Such losses can negatively impact overall system reliability and may cause performance issues in the long run.

The effects of both active and reactive power increases on voltage stability play a crucial role in reliability analysis. Careful management of voltage levels and loading capacities is essential for ensuring system reliability. A reliable electrical grid must maintain both active and reactive power balance to minimize the risks of outages and failures.

4. CONCLUSIONS AND SUGGESTIONS

This study aims to examine an existing power system and model the transmission and distribution networks within this system using the DigSilent program. Furthermore, it seeks to investigate the effects of different scenario studies on network voltage. In the context of the scenario analyses conducted, the impacts of active and reactive power increases on voltage stability were initially evaluated. Active power represents the electrical energy generation within the energy system, whereas reactive power is necessary for voltage control and balancing inductive loads. Therefore, the balanced distribution of these two power components is critically important for ensuring voltage stability. Additionally, the influence of transmission line lengths on voltage levels was also examined. Long transmission lines play a crucial role in transporting electrical energy to remote regions, but their length can increase inductive reactance, leading to voltage drops. To address this issue, it is recommended to use series capacitors on long transmission lines or apply transposition procedures to the lines. Series capacitors are used to balance inductive reactance and prevent voltage drops, while transposition balances the inductive effects of the lines, thereby enhancing voltage stability. Lastly, it should be noted that transformer tap settings can be effectively utilized for voltage control, and this study can serve as instructional material in undergraduate education. Transformers are employed to adjust and maintain voltage levels within the energy system, and this study provides a valuable knowledge resource on voltage management in energy systems for students and professionals in the energy sector.

In a normal state, Bus 6 operates at a voltage level of 34.5 kV with a load of 10 MW. When the active power is increased, it is observed that bus voltages decrease, particularly affecting the bus where consumption has increased. For instance, when the active power reaches 50 MW, the loading capacity of Line 2 increases by approximately 7%.

Similarly, when reactive power consumption is increased, a further drop in bus voltages occurs. The voltage at Bus 6 drops from 0.89 pu at 50 MW of active power to 0.65 pu at 50 MVAr of reactive power. Reactive power transfer analyses reveal that the transmitted values exceed the desired amounts, attributed to increased capacitive reactance losses in the transmission lines. In conclusion, both active and reactive power increases significantly impact voltage stability.

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