TRANSMISSION EXPANSION PLANNING FOR NON-CONVENTIONAL ENERGY RESOURCES

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Abstract: The incorporation of unconventional energy sources, including solar and wind energy, into the grid poses challenging issues for transmission expansion planning (TEP). In contrast to traditional power plants, renewable energy sources (RES) are intermittent, non-dispatchable, and tend to be situated in remote locations with poor transmission facilities. This requires drastic changes in conventional TEP approaches to maintain reliable and economical grid operations. This paper introduces a holistic framework that integrates multiple-objective optimization with production cost modeling to solve complex challenges. The methodology takes into account both technical limitations and economic considerations (investment expense, operational cost savings, and policy-mandated renewable portfolio standards). One of the crucial elements of the study is assessing various scenarios of penetration of renewable energy to identify ideal transmission line upgrades or new installations to ensure adequate capacity for transporting power from remote renewable-abundant areas to high-load load centers. Further, a cost-benefit study is performed to evaluate the financial viability of the expansion plans, balancing initial infrastructure investments with long-term advantages such as lowered generation costs, lower emissions, and better grid reliability. By combining optimization methodologies and scenario planning, this approach offers a sound strategy for building transmission networks for large-scale renewable integration that is still economically and operationally efficient.

Keywords: **:** Renewable Energy Integration, Transmission Expansion Planning, Multi-Objective Optimization, Solar and Wind Power, Grid Reliability, Cost-Benefit Analysis, Sustainable Power Systems .

I. INTRODUCTION

The growing world demand for electricity and the incorporation of renewable energy sources have turned Transmission Expansion Planning (TEP) into a vital component of contemporary power systems. TEP aims to improve the efficiency, reliability, and capacity of transmission networks to meet expanding energy demands. With the development of renewable energy sources like solar and wind power, there is a growing difficulty in maintaining a stable and balanced power supply. This research seeks to offer a strategic transmission expansion strategy that takes into account both renewable and traditional sources of energy generation.

Renewable sources of energy are naturally intermittent, causing fluctuations in power production. The traditional power grids were based on delivering steady power supplies from centralized fossil-fuel-based power plants, whereas contemporary grids have to be more flexible. Incorporating renewable energy involves sophisticated planning of the transmission networks so as not to congest, lose power, and become unstable. In order to resolve these concerns, Transmission Expansion Planning assists in determining the optimal places and sizes of new transmission lines.

The primary aim of this study is to create a MATLAB model of TEP, which optimizes the integration of renewable energy resources and reduces unmet demand in an efficient manner. The method proposed analyzes the existing grid framework, detects zones of power shortage, and outlines the optimal expansion plans. Based on repeated simulations of power flow and demand-supply imbalance, the model proposes the installation of new transmission lines to improve the stability and effectiveness of the grid.

One of the most important elements of TEP is cost minimization. Transmission network expansion is a highly capital-intensive process, involving large investment in infrastructure, material, and manpower. Cost-benefit analysis is used in this study to ensure that expansion is technically feasible as well as economically efficient. With an optimization of energy availability, demand fulfillment, and economic limitations, the model offers a solution for grid expansion that is optimized.

In short, this study outlines a systematic yet flexible approach to Transmission Expansion Planning that can adjust to the dynamic energy environment.The remaining chapters will outline current literature regarding TEP, describe the study methodology, address the simulation outcome, and culminate with insights and suggestions for future research. This research seeks to support the creation of more reliable and effective power delivery networks, especially during the age of rising renewable energy integration.

II LITERATURE REVIEW

Transmission Expansion Planning (TEP) is essential for reliable and economical electricity supply in today's power systems. The classical TEP procedures were deterministic in nature, such as load forecasting, generation expansion planning, and economic analysis. But the rising penetration of variable renewable energy sources (RES) such as wind and solar has made it essential to use more sophisticated planning methodologies. New TEP today includes probabilistic modelling, scenario planning, multi-objective optimization, and new technologies such as energy storage and HVDC transmission to mitigate RES uncertainties.

Renewable integration poses major challenges to TEP. Solar and wind power variability and intermittency introduce grid-balancing challenges, necessitating improved forecasting and flexible generation resources. Geographic spread of RES tends to cause transmission congestion since the available infrastructure is not able to transport power from distant generation points to load centers. Furthermore, economic hurdles such as high upfront investments in transmission upgrades and energy storage make cost-effective integration of renewables challenging. These pose challenges that require innovative solutions in planning and operation.

Technical challenges further compound TEP complexities. Renewable energy sources introduce power quality issues such as voltage fluctuations, frequency instability, and harmonic distortions. Unlike conventional plants, most RES lack inherent grid-support capabilities like reactive power provision, necessitating additional control systems. Policy and regulatory barriers, including inconsistent renewable energy policies and lengthy permitting processes, also hinder efficient transmission expansion. Addressing these issues requires coordinated efforts among utilities, regulators, and technology providers.

To overcome these issues, future TEP will have to utilize new grid technologies like smart grids, wide-area monitoring systems (WAMS), and dynamic line rating (DLR). Energy storage facilities and demand-side management will become critical in compensating for renewable intermittency. This research creates a MATLAB-based TEP model that optimizes transmission expansion along with solving RES integration issues using cost-benefit analysis and scenario-based planning. The following chapters outline the methodology, simulation outputs, and recommendations for developing a resilient grid in the age of renewable energy.

III METHODLOGY

The MATLAB program employs a **Greedy Heuristic approach** to solve the TEP problem. Below, we explain the key methods and their implementation in the program.

The MATLAB program utilizes a Greedy Heuristic Method to address the Transmission Expansion Planning (TEP) problem by iteratively selecting the most effective transmission line additions based on network constraints and demand requirements. The process begins with an initial assessment of the existing transmission network and the identification of unmet demand. The algorithm then evaluates potential transmission line additions, prioritizing those that provide the greatest reduction in congestion and power losses while maintaining system stability. This heuristic approach ensures that each expansion step is both cost-effective and enhances the overall network performance.

As the program iterates, it continuously reassesses the system by identifying the critical paths where bottlenecks occur and determining the optimal locations for new lines. This cycle of evaluation and reinforcement continues until either the network meets the required demand or the predefined iteration limit is reached. By leveraging the Greedy Heuristic Method, the MATLAB program efficiently expands the transmission network, balancing cost considerations with reliability and efficiency. This approach is particularly beneficial for integrating renewable energy sources and ensuring a stable power flow across complex electrical grids.

A. TRANSMISSION EXPANSION ALGORITHM

The The **Transmission Expansion Algorithm** is a structured approach to enhancing the power grid by adding new transmission lines based on system demand, renewable.

Energy integration, and grid reliability. The algorithm follows an iterative process to ensure an optimal expansion strategy while minimizing congestion and improving power quality.

Step-by-Step Process

- **Initialize Input Data**
  - Load the existing power network data, including buses, transmission lines, load demand, and renewable energy generation capacity.
  - Define technical and economic constraints such as line capacity, cost, and power flow limits.
- **Calculate Unmet Demand**
  - Determine the difference between power demand and available generation at each bus.
  - Identify areas where the demand exceeds the available supply.
- **Check Demand Satisfaction**
  - Assess whether the current transmission capacity can meet the demand.
  - If demand is met, proceed to the final network evaluation. If not, continue the expansion process.
- **Identify Critical Path**
  - Analyze power flow and congestion points in the grid.
  - Identify key transmission paths where expansion is necessary to reduce power.
- **Add New Transmission Line**
  - Introduce a new transmission line in the identified critical path based on predefined selection criteria.
  - Ensure that the new line complies with cost, capacity, and grid stability constraints.
- **Repeat Until Max Iterations or Demand is Satisfied**
  - Continue adding new lines iteratively until either the grid meets demand requirements or the maximum allowable expansion is reached.
- **Display Final Transmission Lines**
  - Generate the final network configuration, highlighting the newly added transmission lines.Conduct performance analysis to verify efficiency improvements, reduced congestion, and better renewable energy utilization

B. KEY FUNCTIONS IN MATLABCODE

1. Unmet Demand Calculation (calculate_unmet_demand())

This operation calculates the unmet energy demand at every bus by subtracting the renewable generation from the load and preventing any negative values. It further compensates demand on the basis of transmission line availability. By considering both renewable supply restrictions and grid restrictions, it delivers a pragmatic measurement of energy shortages, which facilitates the analysis of renewable integration efficacy.

2. Critical Path Identification (identify_critical_path())

This action examines the unmet demand data to rank transmission expansion. It ranks buses on their unmet demand and chooses the two most different buses with the largest deficits. This focused process ensures that investments in infrastructure fill the most pressing gaps, making transmission planning have the greatest impact.

3. Complementary Workflow

These functions together create an end-to-end analysis-to-action pipeline:

- calculate_unmet_demand() finds areas of shortage.
- identify_critical_path() finds areas of upgrade need.
  Both provide protections (non-negative demand values, separate bus selection) to provide for useful, error-free implementation.

C. FLOW CHART OF THE EXPANSION PROCESS

The following Fig-1 flowchart visually represents this iterative transmission expansion process:

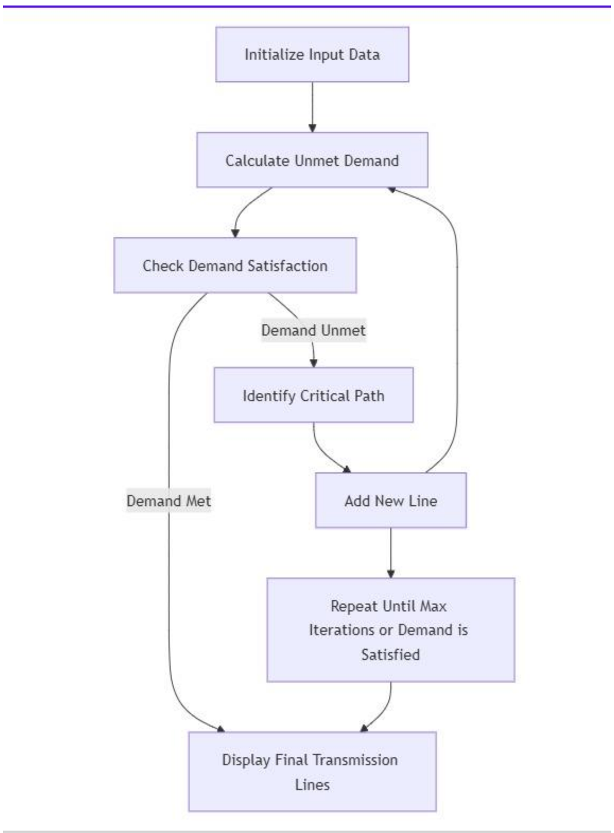

Fig-1 Flowchart of the expansion process

The flowchart visually represents the decision-making process for adding new transmission lines and ensuring effective renewable energy integration

IV RESULT ACHIEVED

A. TRANSMISSION LINE EXPANSION ANALYSIS FOR 3-BUS SYSTEM

The 3-bus test case examines the impact of load and generation variations on the transmission system. Below is the analysis based on the test cases:

The fig-2 represents a three-bus power system network with two generation sources (G1 and G2) and one load point (L3). Buses 1 and 2 are connected to generation sources, supplying power to the network, while Bus 3 serves as a load center, receiving power from both sources through multiple transmission lines. And allows efficient power distribution while maintaining stability and minimizing transmission losses

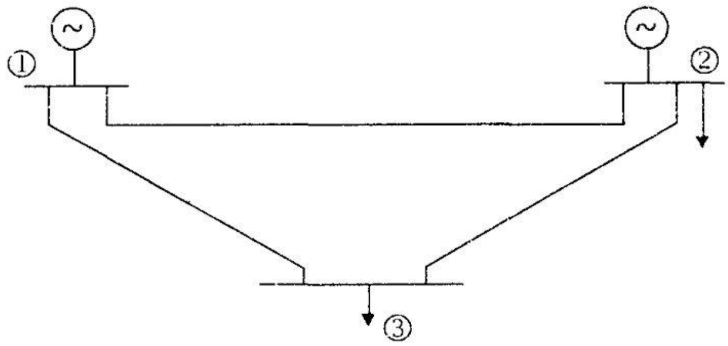

Fig-2: 3-Bus System before adding lines

The updated three-bus power system network fig- 3 shows now includes an additional transmission line from Bus 1 to Bus 3, highlighted in red. This enhancement improves power flow by providing an alternative path for electricity transmission, increasing system redundancy and reliability. With this modification, power generated at Buses 1 and 2 can be more efficiently distributed to the load at Bus 3, reducing transmission losses and enhancing overall network stability.

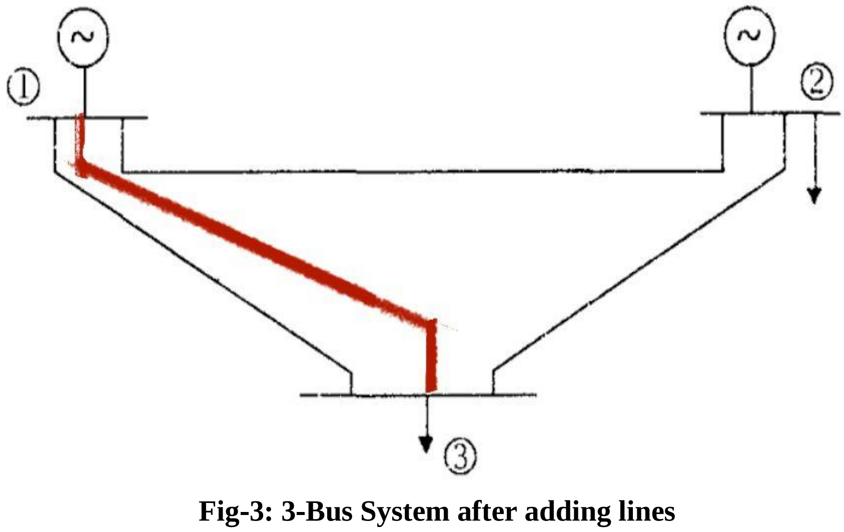

Fig-3: 3-Bus System after adding lines

- **3-Bus System Test Cases**

Scenario	Existing Lines	New Lines	Total Lines
10% Load	3	1	4
10% Gen	3	2	5
25% Load	3	2	5
25% Gen	3	2	5
50% Load	3	3	6
50% Gen	3	2	5
75% Load	3	3	6
75% Gen	3	1	4
100% Load	3	2	5
100% Gen	3	0	3
Gen > Load	3	0	3

Table-1: 3 -Bus Test Case data

B. TRANSMISSION LINE EXPANSION ANALYSIS FOR 6-BUS SYSTEM

The 6-bus system analysis provides critical insights into how transmission expansion is influenced by variations in load and generation. The following observations can be made from the test case data:

The fig-4 represents a six-bus power system network with three generation sources (G1, G2, and G3) and three load points (L1, L2, and L3). The buses are interconnected through transmission lines, forming a structured power flow network. Power generated at buses 1, 2, and 6 is distributed to the loads at buses 3, 4, and 5. The network configuration ensures efficient power distribution while maintaining system stability and minimizing transmission losses.

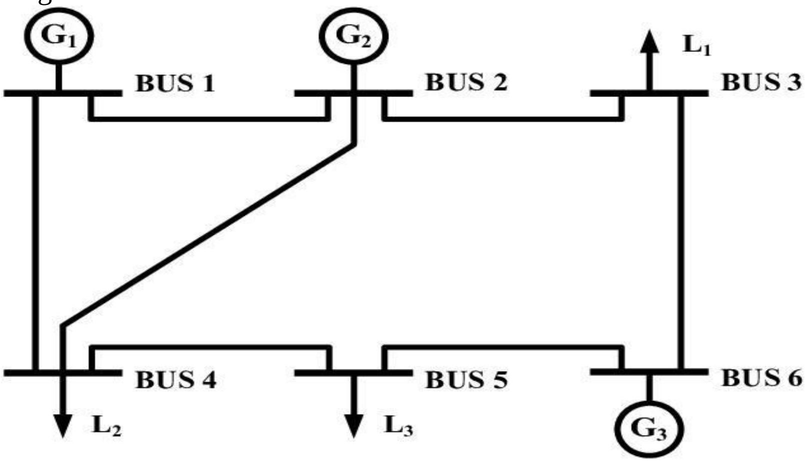

Fig-4: 6-Bus System before adding lines

The updated six-bus power system fig-5 includes additional transmission lines (highlighted in red) to enhance network connectivity and power flow efficiency. These new lines provide alternate paths for electricity transmission, reducing congestion and improving reliability. The added connections help distribute the load more evenly across the system, minimizing transmission losses and enhancing overall stability. This reinforcement ensures that power from generators G1, G2, and G3 is more effectively delivered to the load points L1, L2, and L3, optimizing the system's operational performance.

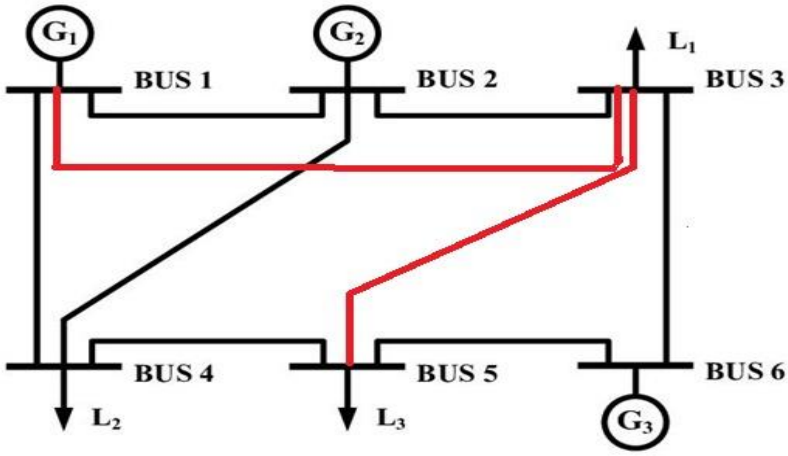

Fig-5: 6-Bus System after adding lines

❖ **6-Bus System Test Cases**

Scenario	Existing Lines	New Lines	Total Lines
10% Load	**6**	**1**	**7**
10% Gen	**6**	**1**	**7**
25% Load	**6**	**2**	**8**
25% Gen	**6**	**1**	**7**
50% Load	**6**	**3**	**9**
50% Gen	**6**	**2**	**8**
75% Load	**6**	**2**	**7**
75% Gen	**6**	**1**	**7**
100% Load	**6**	**3**	**9**
100% Gen	**6**	**0**	**6**
Gen > Load	**6**	**0**	**6**

Table-2: 6-Bus Test Case data

C. TRANSMISSION LINE EXPANSION ANALYSIS FOR 9-BUS SYSTEM

The 9-bus system analysis provides critical insights into how transmission expansion is influenced by variations in load and generation. The study evaluates how the network adapts to increasing demand and generation capacity while ensuring grid reliability, congestion management, and efficient power flow.

The Below fig -6 diagram represents a nine-bus power system network with three generation sources (Gen 1, Gen 2, and Gen 3) and three load points (Load A, Load B, and Load C). The buses are interconnected through transmission lines, ensuring efficient power distribution across the network. Power generated at Buses 1, 2, and 3 is supplied to the loads at Buses 9, 5, and 7 through the transmission network. The system configuration maintains stability and reliability while minimizing transmission losses and ensuring an optimized power flow between generation and load points.

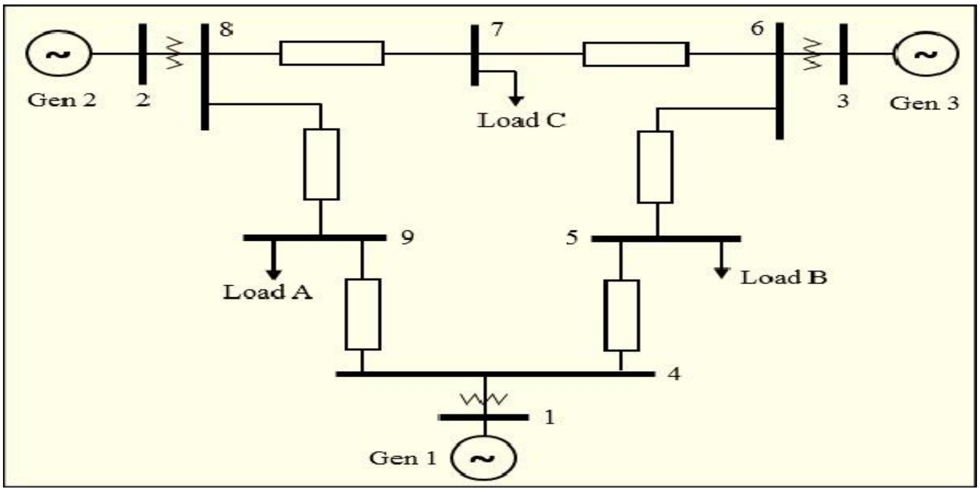

Fig 6 : 9-Bus System before adding transmission lines

The updated nine-bus power system fig-7 includes newly added transmission lines, enhancing connectivity between generation and load points. The new lines establish direct links between Bus 8 and Bus 9, Bus 6 and Bus 5, and Bus 1, improving power flow efficiency and system reliability. With these additions, power generated at Buses 1, 2, and 3 is distributed more effectively to Load A, Load B, and Load C while minimizing transmission losses and ensuring stable operation. The modifications optimize the network's performance by reducing congestion and enhancing voltage stability.

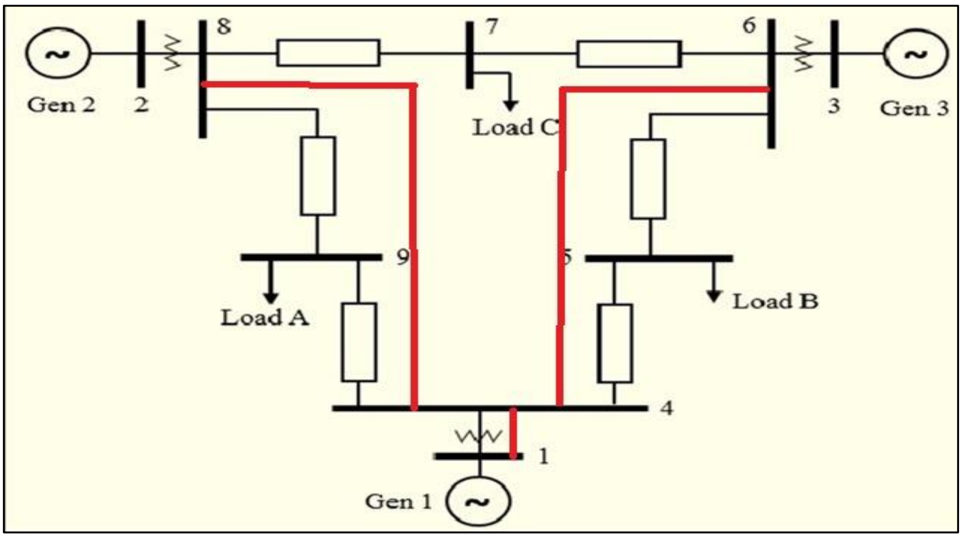

Fig-7 : 9-Bus System after adding transmission lines

- **9-Bus System Test Cases**

Scenario	Existing Lines	New Lines	Total Lines
10% Load	9	1	10
10% Gen	9	1	10
25% Load	9	2	11
25% Gen	9	1	10
50% Load	9	3	12
50% Gen	9	2	11
75% Load	9	2	11
75% Gen	9	1	10
100% Load	9	3	12
100% Gen	9	0	9
Gen > Load	9	0	9

Table 3 : Transmission Line Expansion Table for 9-Bus System

V CONCLUSION

This project successfully analyzed Transmission Expansion Planning (TEP) for Non-Conventional Energy Resources in 3-bus, 6-bus, and 9-bus systems using MATLAB simulations. The study emphasized the importance of an optimized transmission network in ensuring power system stability, reliability, and efficient integration of renewable energy sources.

The findings revealed that as load demand increases, existing transmission lines experience congestion, necessitating the addition of new lines. In the 3-bus system, a 10% increase in load required minimal reinforcements, but higher increases (50%–100%) significantly altered the network structure. Similarly, in the 6-bus and 9-bus systems, higher load increments created more transmission bottlenecks, leading to additional lines being added to relieve network stress. Unlike load growth, generation expansion does not always require major transmission reinforcements unless it results in power flow imbalances. A 10%–50% increase in generation could be managed within the existing network, but higher levels of generation (above 75%) required strategic line additions to accommodate excess power. The 9-bus system demonstrated that a well-distributed generation profile helps in reducing transmission constraints.

Transmission expansion planning must balance cost, reliability, and efficiency while maintaining system stability. Overloading of transmission corridors was prevented by adding new lines in a structured approach, ensuring a smooth power flow. The study also highlighted that non-conventional energy sources, such as wind and solar, require robust transmission networks to distribute power efficiently. Network topology plays a crucial role, as larger bus systems required more complex planning due to increased interconnections. The 3-bus system served as a basic model, demonstrating fundamental expansion strategies, while the 6-bus system provided deeper insights into grid congestion and optimization of power flow under varying demand and generation. The 9-bus system simulated real-world complexity, highlighting the importance of intelligent expansion planning for future power grids.

Looking ahead, this study underscores the growing need for automated and AI-driven transmission expansion planning to handle the complexities of modern power systems. Real-time monitoring and control of transmission networks will be essential as renewable energy penetration increases. Optimization techniques such as genetic algorithms, particle swarm optimization, and machine learning can further enhance expansion planning efficiency.

The findings from this study confirm that a well-planned transmission expansion strategy is essential for meeting future electricity demands while integrating renewable energy sources. The proposed transmission expansion approach ensures that grid stability, structured expansion strategies, power utilities can reduce network congestion reliability, and efficiency are maintained under increasing load and generation conditions. By implementing, improve voltage stability, and enhance overall system performance in a cost-effective manner.

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