Comprehensive Analysis of Power System: Exploring Load Factor, Power Balance, Active Load Variation, and Increment Factors with Iterative Implications

Original Scientific Paper

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Abstract *– The contemporary power landscape is marked by escalating complexity driven by surging energy demands, the integration of renewable sources, and the imperative for heightened system performance. In response to these challenges, this paper presents a thorough investigation. Firstly, the load factor Lambda (λ) is expounded upon, emphasizing its significant impact on system stability due to load characteristics. Static load models are employed for voltage stability studies, providing insights into resource allocation and optimization by comparing actual energy consumption to the maximum potential consumption. Secondly, the paper delves into the power balance, a critical aspect that scrutinizes the equilibrium among generation, consumption, and distribution, underscoring its pivotal role in ensuring system stability. Within a 6-node network, the concept of power balance, denoted as "load λ," is illustrated by tracking its variations across iterations, representing the disparity between Power Generator (PG) and Load (PL). To maintain balance during continuous power flow (CPF) analysis, power supply can be finely adjusted using the load factor lambda (λ). Thirdly, the integration of renewable sources introduces active load variation, underscoring the necessity to comprehend load fluctuations over time for ensuring grid reliability. Active load variation is demonstrated based on the number of iterations. Additionally, the paper elucidates the increment factor τ, explaining its impact on the number of correction iterations by selecting the size of the step factor. The graphical representation of the increment factor for iterations 8 and 11 in a network with load nodes provides further clarification. This paper explores the intricate interactions of load factors, power balance, active load changes, and increment factors within power systems. The presented findings contribute to the enhancement of the reliability, efficiency, and sustainability of modern power systems.*

Keywords: *Power System Analysis, Load factor, Power balance, Active Load Variation, Increment Factor*

1. INTRODUCTION

This paper presents a comprehensive investigation into various critical dimensions that collectively influence the behavior and performance of modern power systems. With a focus on addressing energy needs and the integration of renewable sources, our analysis encompasses key aspects of power systems, including Load Factor (λ), Power Balance, Active Load Variation, and Increment Factors (τ). These dimensions play a pivotal role in guiding decisions for the efficient, reliable, and sustainable operation of power systems. Efficiency and resource allocation within power systems are crucial considerations, and our paper quantifies efficiency by comparing actual energy consumption to potential usage. Emphasizing the significance of maintaining equilibrium among generation, consumption, and distribution, we delve into the role of this balance in ensuring system stability and an uninterrupted power supply. In exploring load patterns, particularly with the integration of renewable energy, our study investigates their fluctuations and the ensuing impact on power system reliability. Furthermore, we examine how small adjustments in increment factors can significantly influence power system responses under varying conditions, taking into account the iterative nature of these adjustments. The paper aims to provide a holistic understanding of the interconnected nature of load factors, power balance, active load variation, and increment factors within contemporary power systems. By doing so, it seeks to contribute to informed decision-making that optimizes the reliability, efficiency, and sustainability of power systems in the ever-evolving energy landscape.

The Load Factor (λ), examined in [1-3], plays a pivotal role in evaluating energy efficiency and resource allocation. As investigated in [4-7], the Power Balance highlights its crucial significance in maintaining system equilibrium. Active Load Variation, explored in [8, 9], [10], delves into the fluctuations in load patterns and their consequential impact on system stability and reliability. Increment Factor, examined in [11-13], contributes to understanding its role in power system responses to varying conditions. These cited references collectively form the foundation for a comprehensive analysis of these dimensions within power systems. References [14-16] collectively contribute to the advancement of power system analysis. In [14, 15], a detailed analysis assesses the scalability and performance of a proposed formulation on a substantial 2383-bus Polish test network. Reference [16] investigates maximum loadability and transfer capability in a Power System (PES) through systematic load condition adjustments. For a detailed understanding of security, reliability in power system stability, including its definition and classification, refer to [17-20].

In [1], load characteristics play a crucial role in system stability. CPF analysis incrementally raises the load using the load factor Lambda (λ) before each iteration, beginning from base load values Po, Qo. Accurate step factor adjustments are essential for corrector convergence along the power-voltage (PV) curve, identifying the stability limit by the sign change of dLambda. Notably, convergence slows near the critical point, particularly in its vicinity. Moreover, corrector convergence is swifter with the continuous parameter λ than with the continuous parameter V.

In [2], the calculation of network reliability involves simulating interruptions of network components (lines, transformers, buses) and analyzing the effects of failures, including checking for violations of voltage, current, and reactive power limits.

In [3], incorporating the continuation technique into load flow analysis requires integrating the load parameter lambda (λ) within the equations. This is especially pertinent for models with constant load characteristics. Both the load (indexed as L) and generation (indexed as G) at a node depend on the load parameter.

To replicate load fluctuations, adjustments are applied to load values PLi and QLi. Changes in active power generation follow the equation: $PGi = PGio$ (1 + $KGi\ \lambda$), where $PGio$ represents the active generation at the node during the base scenario. The constant KGi is utilized to calibrate the degree of generation adjustment [4].

The selection of the projected step factor's magnitude is tailored to align with the existence of a load flow solution, as dictated by the provided continuous parameter. If an iteration fails to converge with the current step factor size, the magnitude is systematically decreased. This corrective process is reiterated until a solution is successfully obtained [5].

In [6], the characterization of nodes within an electrical network identifies three primary types: reference node (slack node), PQ (load node), and PV (generator node). The reference node plays a crucial role in maintaining the power system's equilibrium.

In a steady-state balanced power system, as outlined in [7], requirements include meeting generation demands, maintaining bus voltage levels, operating generators within specified power limits, and preventing overloading of transmission lines and transformers.

In references [8] and [9], the analysis focuses on the stability of voltage in electrical power networks, emphasizing the importance of maintaining voltage within permissible limits. This is particularly significant as networks may encounter voltage fluctuations due to the continuous expansion of renewable energy sources. The paper further investigates the causes of voltage drop and explores measures taken by consumers, actions implemented in the network, and generation-related strategies to mitigate these effects.

In [10], a novel method is presented for controlling DC bus voltage in a hybrid energy storage system, contributing to enhanced stability and reliability for renewable energy systems.

In [11], the iterative process involves selecting the size of the projected step factor in a manner that aligns with the existence of a load flow solution based on the continuous parameter. If an iteration fails to converge with the current step factor size, an adaptive approach is employed, systematically reducing the magnitude until a successful solution is achieved.

In [12], an analysis of the transmission system's role in voltage stability is presented, focusing on two fundamental concepts: the maximum power deliverable to the loads and the relationship between load power and network voltage. Failure to meet these essential criteria can lead to voltage instability.

In [13], the CPF algorithm's step length control is crucial for efficiently identifying the nose point. This control offers a choice between a constant or adaptive approach, providing flexibility to overcome convergence challenges as the system nears its loading limit. As the curve approaches the loading point's pinnacle, step sizes naturally decrease, refining the trajectory toward maximum loading conditions.

In [14, 15], an exhaustive examination was conducted, presenting a detailed and comprehensive analysis of the scalability and performance assessment of a proposed formulation. This evaluation was executed on a sizable 2383-bus Polish test network, maintaining loading conditions from a 30-bus test case. The findings showcased the robustness of the formulation, with a particular focus on the LU transversality condition and the behavior of geig. The study emphasizes the significance of the network size in influencing the convergence rates for gLU and $geig$, while gQR and gsvd demonstrated a more consistent performance, less dependent on the network size. Moreover, adjustments in the Newton step size (α) were imperative for convergence in larger test cases.

In [16], the study investigates the maximum loadability and transfer capability in a Power System (PES) through systematic adjustments of load conditions at each bus. This allows for loadability assessment under three scenarios: Scenario 1 explores maximum loadability without technical constraints, Scenario 2 introduces voltage magnitude constraints, and Scenario 3 adds constraints on generation power output, line thermal limits, and voltage magnitude. The paper focuses on assessing interconnection feasibility, aiming to determine the maximum surplus capacity (estimated at around 200 MW) available for export to the Democratic People's Republic of Korea (DPRK), without compromising the security and stability of the PES grid. The analysis considers strict constraints on voltage levels, active and reactive generations, and line limits for system reliability. Results in [16] reveal a maximum loadability margin (λmax) of 2.8854 and a Total Transfer Capability (TTC) of 57.71 MW, offering crucial insights into operational limits and potential interconnection opportunities.

In [17], key power system security analysis methods, voltage stability investigation, and their integration into reliability analysis are highlighted. The real power system operating near capacity, along with the evaluation of measures to enhance reliability, is discussed for a clear overview.

In [21], the focus is on the selection and control of the step size, a crucial factor for the success of continuous power flow. Flexibility in step size control is paramount to adapting to the power system, thereby facilitating strong convergence. The introduction of the load parameter lambda results in the formation of the nonlinear equation $F(V,\delta_2)\ \lambda,) = 0$.

In [22], the paper introduces a cost-effective power factor (PF) metering system using an Arduino microcontroller, emphasizing the importance of power factor in preventing energy costs and outages.

The remainder of the paper is structured as follows: Section 2 provides a detailed explanation of the methods used. Section 3 presents the Results, which are divided into four subsections: Subsection 3.1 analyzes the load factor λ. Subsection 3.2 examines the balance of power as a function of the number of iterations. Subsection 3.3 demonstrates active load as a function of the number of iterations. Subsection 3.4 illustrates the increment factor τ and explained with an example. Section 4 presents the Conclusions.

2. METHODS: LOAD FACTOR, POWER BALANCE, AND ITERATION-RELATED PARAMETERS

2.1 THE LOAD FACTOR (λ) IN CPF.

Four operating states, namely Normal, Vulnerable, Disturbed, and Recovered, are conventionally established to ensure the safety of the electrical network. Transitions between these states also play a significant role.

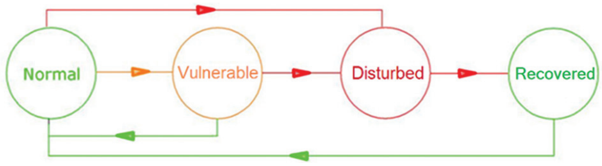

Fig. 1. The states of an energy network

A steady-state balanced power system necessitates adherence to the following conditions: Generation must satisfy both demand (load) and losses, bus voltage magnitudes should remain close to their rated values, generators must operate within specified limits for real and reactive power, and transmission lines and transformers must avoid overloading.

The stability of the system relies significantly on load characteristics. Studies on voltage stability often utilize static load models, including constant power, constant current, or constant impedance models. Additionally, load models may incorporate polynomial functions with voltage magnitude as a parameter [1].

The interplay between the concepts of power system reliability, security, and stability is extensively discussed in both theoretical frameworks and practical applications, as elaborated upon in more detail in reference.

In general, an electrical network is considered safe when the generation capacity surpasses the cumulative load demand, transmission elements operate within specified load thresholds, node voltages adhere to acceptable limits, the network exhibits resilience against generator failures ensuring continued functionality, the network accommodates transmission line losses without significant repercussions, and stability prevails within the network even under short-circuit conditions.

The load characteristic in voltage stability analysis is modeled by a function that expresses the active and reactive power in terms of the voltage magnitude (V) and an independent variable (λ), referred to as the load change parameter: $P = P(\lambda, V)$, $Q = Q(\lambda, V)$. Security refers to the network's capacity to withstand unforeseen disturbances, such as short circuits or unexpected component losses [18-20].

It effectively communicates that in the context of CPF analysis, the Load Factor (λ) plays a crucial role in evaluating system behavior and stability. It also highlights the impact of varying load factors on different aspects of power systems in CPF scenarios.

In CPF analysis, the Load Factor represents the degree of load demand on the system relative to its rated capacity. It directly affects voltage profiles and load distributions. A higher load factor places the system closer to its capacity limits, raising concerns about voltage stability and system reliability. Understanding the interplay between load factor variations and system stability is paramount in CPF analysis. Voltage stability is a central concern in CPF studies. Load factor variations can lead to voltage instability or even collapse. By examining the correlation between load factor increments and voltage stability margins, we gain insights into critical load factor thresholds that signal potential voltage instability.

2.2 BALANCE OF POWER AS A FUNCTION OF THE NUMBER OF ITERATIONS IN CPF

Understanding power balance in CPF scenarios is crucial for comprehending the system's behavior as conditions evolve. The power balance undergoes changes with an increasing number of iterations in CPF analysis. Investigating this evolution provides valuable insights into how power distribution adjusts in response to changing conditions. Observing power balance trends over iterations aids in predicting convergence behavior and helps identify scenarios where the balance is compromised. Through iterative analysis, the Balance of Power helps gauge the system's stability during CPF iterations. Deviations from balanced power conditions can signify instabilities or impending voltage issues. By correlating power balance variations with system response, we gain a deeper understanding of how the system adapts and stabilizes under different loading scenarios. Electric power systems, by their nature, require a delicate equilibrium, where electricity demand aligns precisely with supply at all times.

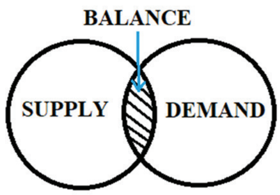

Fig. 2. Supply-Demand balance

In electrical power systems, maintaining a delicate equilibrium between supply and demand is crucial to prevent grid failures. Employing adaptive mechanisms becomes imperative to counteract fluctuations and ensure the system's stability. System operators play a pivotal role in this process, continuously monitoring relevant parameters to prevent any disturbances beyond specified threshold limits [7, 22].

2.3 ACTIVE LOAD IN THE FUNCTION OF THE NUMBER OF ITERATIONS.

In the realm of CPF analysis, a profound comprehension of how active load variations influence system behavior is paramount for accurate predictions and decision-making. Active load variations exert a direct impact on power distribution and voltage profiles. Observing the influence of active load changes on system response over iterations unveils discernible patterns, facilitating effective load management strategies. The analysis of active load enhances our ability to maintain balanced power conditions, preventing undue stress on components.

The resilience of the system in CPF analysis is significantly influenced by active load variations. A sudden surge in active load can lead to overloading and voltage instability. The study of the intricate relationship between active load, iteration count, and system response enables the identification of critical points where interventions such as load shedding or redistribution may be imperative to ensure the integrity of the system [5, 12].

2.4 THE INCREMENT FACTOR τ

The Increment Factor Tau (τ) dictates the rate at which power flow adjustments occur during CPF iterations. A well-chosen tau value ensures convergence while preventing oscillations. The selection of tau significantly impacts the stability of CPF analysis, necessitating a careful balance between rapid convergence and system stability. We define the Increment Factor τ as a critical parameter controlling the rate of power flow adjustments during CPF iterations, influencing iteration convergence and stability. This passage outlines the strategy employed to select appropriate values for the Increment Factor τ.

In the Predictor step, the main goal is to calculate the tangent vector component, represented as 't.' The estimated predictor can be computed as follows

$$\begin{bmatrix} \underline{\delta_i} \\ \underline{V_i} \\ \lambda_i \end{bmatrix} = \begin{bmatrix} \underline{\delta_{(i-1)}} \\ \underline{V_{(i-1)}} \\ \lambda_{(i-1)} \end{bmatrix} + \tau \begin{bmatrix} d\underline{\delta} \\ d\underline{V} \\ d\lambda \end{bmatrix} \tag{1}$$

Tau (τ) is symbolically represented as a scalar, serving as the step size factor in Equation 2.

$$\underline{It}_{ip} = \underline{it}_{(i-1)} + \tau * \underline{t} \tag{2}$$

$\underline{It}_{ip}$ refers to values after the predictor step, while $\underline{it}_{(i-1)}$ represents initial values before the predictor step, where 'i' is the iteration number. The estimated predictor step values require subsequent correction [8, 9].

3. RESULTS: LOAD FACTOR, POWER BALANCE, AND ITERATION-RELATED ANALYSIS

3.1. THE LOAD FACTOR λ.

During the course of analyzing the CPF, the load increases with the load factor λ before each CPF iteration, starting from the base load (P_0, Q_0), for example, in the 17-node network with λ=0.15.

$P_0$5=1.00; $Q_0$5=0.80; K=1.0

P5=$P_0$5 (1+$K\lambda$)*100= 1.0*1.15*100 = 115 MW,
Q5=$Q_0$5 (1+$K\lambda$) *100= 0.8*1.15*100 = 92 MW.

K is a calibration factor that can be assumed differently for active and reactive loads, and it can also vary for individual nodes. However, in the present investigations, it is consistently set to 1.0.

To ensure that the balance (supply–load) remains stable during the CPF analysis, the supply can also be increased proportionally with the load factor. However, this adjustment did not occur in all calculated networks. In cases where supplies were kept constant, the load increased and shifted to the reference.

Table 1. Active and Reactive Power values for iterations 1,14,19, and 32 at Node 5 in the 17-node Network.

Iteration	P5 (MW)	Q5 (MVAr)
Initial ($\lambda = 0$ p.u.)	100	80
1st ($\lambda = 0.15$ p.u.)	115	92
14th ($\lambda = 3.1817$ p.u.)	418.17	334.536
19th ($\lambda = 3.1547$ p.u.)	415.47	332.376
32nd ($\lambda = 0$ p.u.)	100	80

In Table 1, it is observed that the load reaches its maximum (critical point) in iteration 14 with a load factor (λ) of 3.1817. By iteration 32, the base load is once again attained, but the operating point is now on the lower part of the PV-curve.

3.2. BALANCE OF POWER AS A FUNCTION OF NUMBER OF ITERATIONS

In Fig. 3, during the first iteration, the load (PL) is 10 MW. Since the generated power (PG) remains constant for all iterations, there is a surplus of 90 MW in the grid, sourced from the slack node.

As lambda increases, the load on the grid rises to 30 MW in iteration 2. The power difference between generation and load gradually decreases, reaching zero by iteration 5. Starting from iteration 6, the grid load surpasses the generation, and the difference is supplied from the reference node.

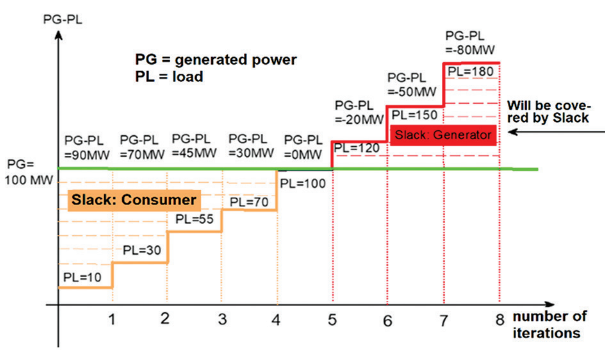

Fig. 3. Power balance PG-PL as a function of the number of iterations. Orange: Slack is a consumer; Red: Slack is a generator.

3.3 ACTIVE LOAD IN THE FUNCTION OF THE NUMBER OF ITERATIONS

Fig. 4 presents the active load ('Load') in the 6-node network as a function of the number of iterations.

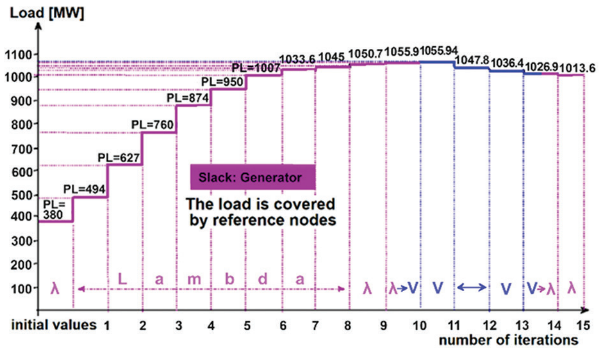

Fig. 4. Network load as a function of the number of the iterations in the 6-node network (Load)

The network consists of 3 load nodes with no additional supply except for the reference node (slack). In Iteration 1, this covers a grid load of 380 MW. From Iteration 1 to 9, the parameter lambda (λ) is treated as a continuous parameter (depicted in purple). In Iteration 10, there is a transition from the parameter lambda (λ) to V ($\lambda \rightarrow V$).

From Iteration 11 to 13, the voltage V is employed as the continuous parameter (depicted in blue). In Iteration 14, there is a shift from parameter V to λ ($V \rightarrow \lambda$) once again (depicted in purple, representing the lower part of the curve). The load reaches its maximum in Iteration 11, marking the critical point, and the descending part of the load curve corresponds to the lower part of the PV curve. Fig. 3 displays only 15 out of the total 24 iterations.

3.4. INCREMENT FACTOR τ

There is a tendency for the corrector to converge more slowly the closer it gets to the critical point. Furthermore, the corrector converges more slowly with the continuous parameter V than with the continuous parameter λ. Slow convergence also occurs when the condition to change the continuous parameter λ to V is fullfilled by multiple nodes simultaneously. Therefore, in order to achieve convergence of the corrector in each part of the PV curve, the size of predicted step factor must be adjusted in each CPF iteration. When the critical point approaches, it reduces; after it exceeds (in the lower part of the PV curve), it can be increased again. For example, in the case of a 6-node network near the critical point, with a step size factor τ=0.01, approximately 8 corrector steps are needed for the iteration to converge.

If the step size factor is reduced to τ=0.0075, only 5 correction steps are required, as illustrated in brown in Fig. 5.

The increment factor for iterations 8 and 11 in the 6-node network labeled 'Load'

In Fig. 5, the impact of the selection of the step factor size on the number of correction iterations is illustrated. Ideally, each iteration should converge within 4-5 iterations for a given step factor size. The brown color in Fig. 5 indicates the increased number of iterations due to the larger step factors.

For a step size factor of 0.03, 5 correction steps are required for convergence. Increasing the step size from τ=0.03 to τ=0.035 necessitates 6 corrector iterations. In iteration 11, voltage V4 serves as a continuous parameter. With an increment factor of τ=0.025, only 2 correction steps are necessary. If the step size factor is then increased to τ=0.035, the corrector converges in just 3 iterations. It's important to note that if the selected step factor is too small, while reducing the number of correction iterations, it significantly increases both the number of CPF iterations and calculation time.

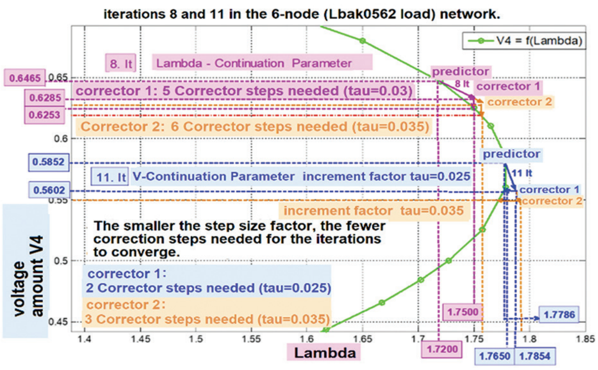

Fig. 5. Step size factor (τ) for iterations 8 and 11 in a 6-node network labeled 'Load'.

In the CPF iteration 8, the parameter lambda is used as a continuous parameter.

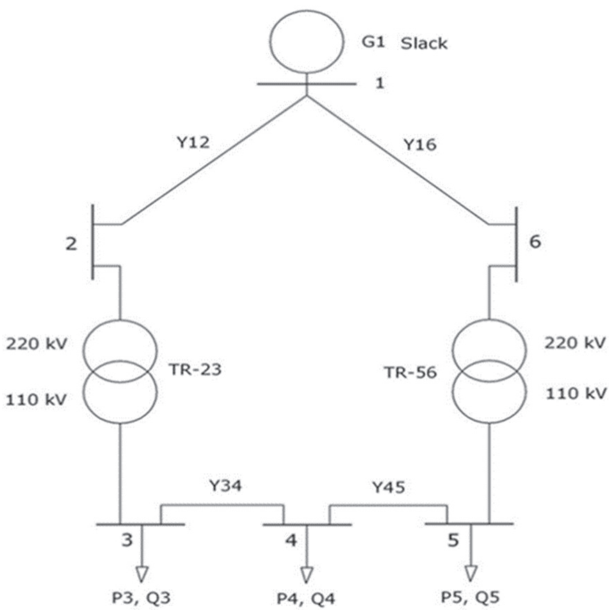

Fig. 6. 6-node network labeled 'Load'

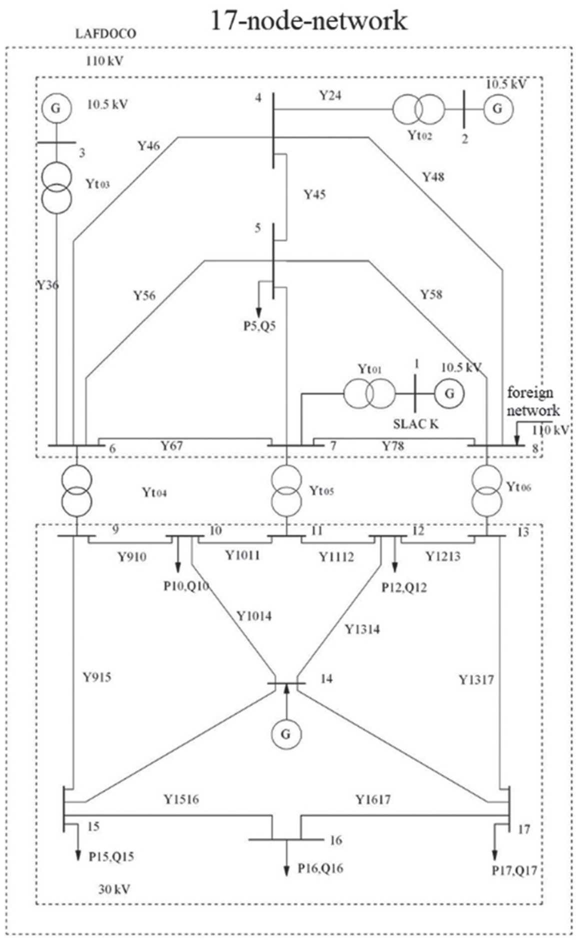

Fig. 7. 17-Node Network

4. CONCLUSIONS

In this paper, we investigate the interdependencies shaping power system behavior. Our comprehensive exploration, spanning load factor, power balance, active load variation, and increment factor, yields valuable insights that contribute to an enhanced understanding of power system operations.

Firstly, the load factor Lambda (λ) is explained. The examination of load factor λ emphasizes its significance in evaluating system efficiency and utilization. By comparing actual energy consumption to the maximum potential consumption, it provides a clear assessment of resource management, essential for optimizing power generation and distribution.

Next, the practical demonstration of power balance in the network is explained and demonstrated over several iterations.The balance is depicted by the difference between Power Generator (PG) and Load (PL). To maintain balance during CPF analysis, supplies can be increased with the load factor lambda (λ). When supplies are constant, load increases shift to the reference node. This investigation highlights the pivotal role of power balance in maintaining system stability

Third, the study of active load variation has highlighted the challenges posed by the integration of renewable sources. Understanding load fluctuations over time is crucial for adapting grid strategies and ensuring a reliable electricity supply. Practically, through an example in the 6-node network, "$Load$" is calculated using the CPF program, demonstrating the active load as a function of the number of iterations.

Finally, the analysis delves deeper into the increment factor τ, illustrating the influence of the step size factor on correction iterations. Graphical explanations for iterations 8 and 11 in a 6-node network (Load) are provided. Increased step size requires more correction steps for convergence, while a too-small factor reduces correction iterations but significantly extends CPF iterations and calculated time. This analysis underscores the crucial role of increment factors τ in optimizing power system performance.

The interaction among load factors, power balance, active load variation, and increment factors unveils complex system connections. This understanding facilitates the development of strategies to improve the reliability, efficiency, and sustainability of modern power systems. The insights gained contribute to optimizing power system performance, supporting a smooth transition toward a future of reliable and sustainable energy supply in the evolving energy landscape.

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