Enhancing voltage stability of transmission network using proportional integral controlled high voltage direct current system

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ABSTRACT

The contingencies experienced in transmission power networks often lead to unstable voltage profiles, challenging grid reliability and stability. This research aim is to enhance voltage stability using a proportional-integral (PI) controlled high voltage direct current (HVDC) system on a real life 330 kV network. The Newton-Raphson (NR) method is used for power flow analysis of the test network, and stability analysis identified Makurdi bus as the candidate bus for improvement due to its low eigenvalue and damping ratio. Application of a balanced three-phase fault at this bus resulted in a minimum voltage of 0.70 per unit (p.u.), falling outside the statutory voltage limit requirements of 0.95 to 1.05 p.u. The PI-based HVDC system was then applied along the Makurdi to Jos transmission line, which has a low loading capacity. The application of this model optimized the system response to disturbances, significantly improve voltage stability and raised the minimum voltage profile on the network to 0.80 p.u. This demonstrates 10% voltage profile improvement from the base case and reaffirms the effectiveness of the PI-based HVDC system in enhancing voltage stability during major disturbances. This research highlights the potential of integrating control systems into power networks to improve voltage stability and ensure reliable operation, even during large disturbances.

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1. INTRODUCTION

Voltage stability is a critical concern in the operation of modern power systems, particularly in multi-generator networks where the complexity and interdependencies of various components can lead to significant challenges in maintaining stable voltage profiles. As power systems continue to grow in scale and complexity, driven by increasing demand and the integration of renewable energy sources, the risk of voltage instability becomes more pronounced [1]. This instability can result in voltage sags, swells, or even catastrophic blackouts, making it essential to implement robust control strategies that can enhance voltage stability across the network. One promising approach to address these challenges is the integration of high voltage direct current (HVDC) systems. The HVDC system is notable for its ability to efficiently transmit large amounts of power over long distances, and when combined with a good control technique, they offer a powerful solution for enhancing voltage stability [2]. The proportional integral controller ability for adaptive tunning and handling nonlinearities can optimize the operation of HVDC systems in real-time, ensuring that the voltage levels within the power system remain stable under varying load conditions and disturbances. Similarly, the increase in power outages due to scheduled maintenance, severe load variations, natural forces and an increase in demand has caused electromechanical oscillations in power systems and have pushed many power networks into an unstable state of operations [3].

Contingencies in the alternating current (AC) power network have caused the tripping of power lines, isolation of generating stations and reconfiguration of the entire network, leading to instability in the network [4]. These contingencies reduce the network strength and have caused adverse interactions of HVDC systems on a connected grid [5], [6]. To eliminate these effects, guidelines and methods for voltage stability assessment of an HVDC-connected AC network are introduced. Power systems are designed to transmit electricity efficiently, but many transmission networks suffer from poor infrastructure, leading to significant challenges for engineers, customers, and utility companies. The power system network typically consists of generation, transmission and distribution sections. An interconnected transmission network is essential for delivering electricity over long distances to meet energy demand [7], [8]. However, traditional AC transmission networks face several limitations when transmitting huge amounts of power over a long distance; it causes voltage drop and power loss along the lines. To address these issues, dynamic stability assessments are crucial, especially as the problem has left many energy consumers without grid connection [9]. Voltage stability refers to the ability of a power system voltage profile to return to the operating limit after a fault occurs. The stability here is in reference to the bus voltage profile, which must operate within ±5% (from 0.95 p.u. to 1.05 p.u.).

2. REVIEW OF RELATED LITERATURE

There has been a lot of interests in enhancing transmission system for sustainable and reliable electricity supply. Therefore, different methods have been suggested by researchers to enhance the voltage profile of a multi generator power system like the Nigeria 40 bus 330 kV transmission network but only a few have applied an automatic tuning technique in this approach. Aneke and Anzaku [10] applied the modal/eigenvalue analysis technique to improve the voltage stability of the 330 kV, 48-bus power system network in Nigeria. They simulated the network under both static and dynamic loads, conducting modal/eigenvalue analysis under varying load conditions. The results showed that increased loads at three identified vulnerable buses led to reduced system stability. The study demonstrated that reactive power compensators could significantly improve the voltage profile of a network. However, the authors did not consider the need for a regulated HVDC system or the use of an intelligent approach, such as proportional integral controller for enhancing voltage stability. Furthermore, Van Custem [11] highlighted two important aspects of voltage instability within power systems, their work demonstrated that voltage stability can be significantly compromised by the tripping of key generation or transmission equipment, which disrupts the balance of power supply and demand. A low voltage profile within any power system is a primary precursor to such blackouts, typically caused by voltage collapse as stated in [12], [13]. When a transmission line trips, the remaining lines must carry the additional load, which increases the consumption of reactive power. This heightened demand for reactive power leads to a further decline in voltage levels, exacerbating the risk of a complete voltage collapse [14]. Several factors contribute to the likelihood of a blackout, including weak grids, adverse climatic conditions, sudden changes in load, systems that are heavily loaded beyond their capacity, and human errors [15]–[17]. Each of these elements can initiate a cascade of failures, ultimately leading to a catastrophic loss of power across the network.

These failures reinforced the need for the implementation of a HVDC system for voltage stability enhancement in a multi-generator power network like the Nigeria 330 kV 40 bus transmission networks. The HVDC transmission system has been extensively studied for its capability to transmit large quantities of electricity over long distances while minimizing power losses. A key study [18] explores the effectiveness of HVDC systems in reducing transmission losses, highlighting their advantages over traditional AC transmission systems, particularly in long-distance applications. Another study [19] goes further by calculating and simulating power losses in HVDC transmission lines using two distinct models, providing valuable insights into the efficiency of HVDC systems under different operating conditions. Similarly, study [20] introduced an innovative approach by proposing a novel DC/DC converter designed to link multiple DC grids operating at various voltage levels. This converter not only facilitates the interconnection of different DC networks but also actively controls the power flow between them, enhancing the overall efficiency and flexibility of the power system. Additionally, another study [21] demonstrated the positive impact of integrating HVDC links and bipolar connections into a power system, particularly in terms of enhancing the voltage profile. Their study also considered various load scenarios to thoroughly assess the system voltage stability and power loss under different conditions. Further research [22] presented a method involving the simultaneous adjustment of active and reactive loads across all load buses. This approach was used to simulate stressed conditions in load flow analysis, particularly utilizing a static synchronous compensator (STATCOM) device to analyze the behavior of a system to disturbances. Similarly, a study [23] simulated the integration of an HVDC network and found that power losses decrease as demand increases, showcasing the efficiency of HVDC in handling growing loads. The combined AC and voltage source converter multi terminal direct current (VSC-MTDC) systems optimal power flow was also examined in [24], demonstrating a significant reduction in active power losses and highlighting the growing influence of HVDC technology on the transmission grid. A proposed network reconfiguration strategy aimed at improving the voltage profile and reducing transmission losses in practical utility transmission networks underscored the importance of strategic planning in enhancing system performance [25], [26].

This paper focuses on using an automated tunning proportional integral based HVDC system to improve the voltage stability of a transmission network when subjected to a balanced three-phase fault. Many research papers reviewed have not considered this technology for voltage stability improvement. The balanced three-phase fault in this research is considered a large disturbance that threatens the transmission network stability in achieving steady state operation of generators and sustainable power supply. The remaining sections of this paper are organized as follows: Section 3 presents the materials and methods employed for the analysis conducted in this research. Section 4 discusses the results obtained through the application of the proposed method, highlighting the improvements achieved in the network. Finally, section 5 summarizes the key findings and concludes the study.

3. MATERIALS AND METHOD

The power system analysis toolbox (PSAT) is a power system software used for modelling of power components, devices and networks inside MATLAB/Simulink. In this paper, it is used to model a single line diagram of a 40 bus 330 kV Nigeria transmission network as shown in Figure 1. The network data including bus, generator, line and load data were obtained from the national control center of the Nigeria transmission company. The data obtained is the most recent network data for sake of credibility and accuracy which is used to conduct power flow studies, eigenvalue analysis, and dynamic studies of the network to identify critical buses and weak transmission lines during fault conditions. An iterative technique called the Newton-Raphson method, is applied to solve the power flow equations during analysis. These power flow equations are nonlinear algebraic equations that define the relationship between bus voltages and power flows within the network. The objective is to determine the bus voltages that meet the specified power injections or extractions at each bus. The balanced three phase fault is applied at a specified candidate bus and the load flow study of the network was conducted to determine the behavior of the network under the influence of a large disturbance.

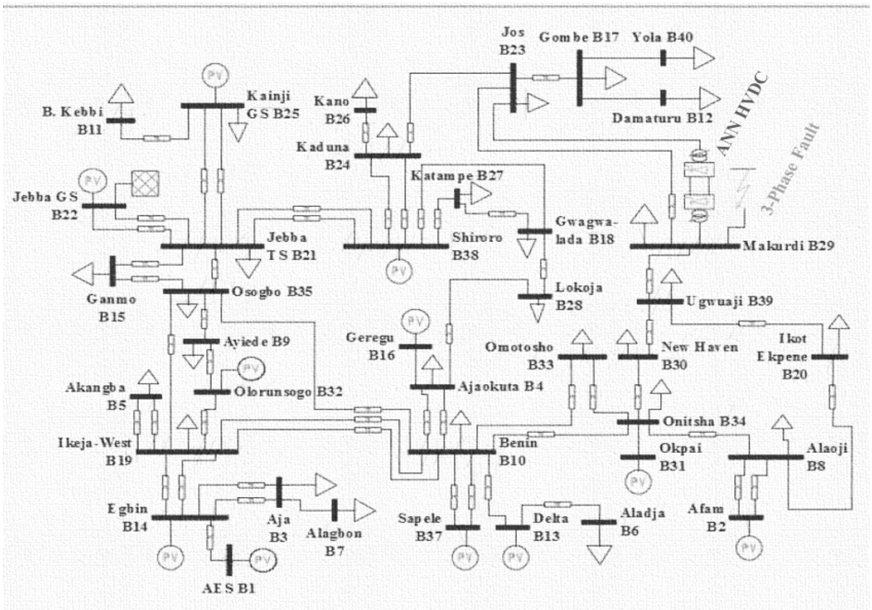


Figure 1. Single line diagram of a 40 bus Nigeria transmission network

3.1. The power flow analysis of the test network

In a large transmission network, the mathematical representation of the power flow is determined by the current injection at various nodes in the network and analyzed using the power flow techniques. The injected current at bus i is given as I_i while the voltage is determined using (1).

$$V_i = |V_i|\ell^{j\delta_i} \tag{1}$$

The current at bus k is given as (2),

$$I_k = \sum_j^n Y_{kj} V_{kj} \tag{2}$$

Where Y_{ii} is the mutual bus admittance matrix. There is a complex bus in the network denoted by k. Therefore, the apparent power of the network becomes,

$$S_k = P_k + jQ_k \tag{3}$$

The V_k and V_j are the voltages at the buses. The real and reactive power of the network is given as (4).

$$P_k + jQ_k = V_k * I_k^* \tag{4}$$

The node current

$$I_k = \frac{P_k + jQ_k}{V_k^*} \tag{5}$$

The I_k^* and V_k^* represents the current and voltage conjugates of I_k and V_k respectively. Hence, the node voltage is given as (6).

$$V_k = \frac{1}{Y_{kk}}\left[\frac{P_k + jQ_k}{V_k^*}\right] - \sum_{j\neq 1}^n Y_{kj} V \tag{6}$$

Also, the real P_i and Q_i power at any bus is denoted in (7) and (8). This is the power flow through the transmission lines from bus i to j.

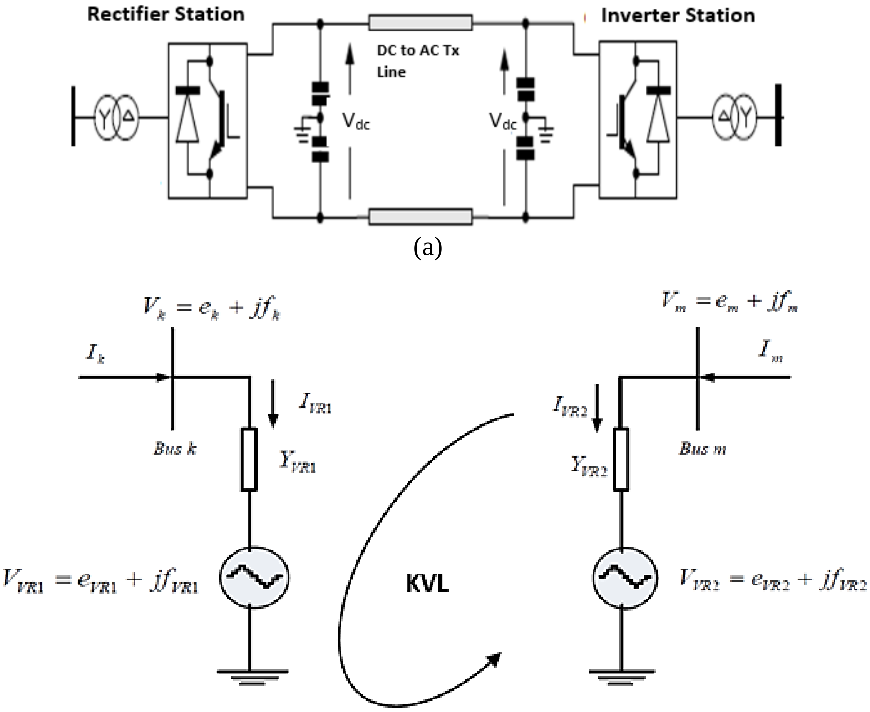
$$P_i = Re\left[V_i^*\left[Y_{ii}V_i + \sum_{j=1} Y_{ii}\left(V_i - V_j\right)\right]\right] \tag{7}$$

$$Q_i = Im\left[V_i^*\left[Y_{ii}V_i + \sum_{j=1} Y_{ii}\left(V_i - V_j\right)\right]\right] \tag{8}$$

3.2. The HVDC system modelling for a multi-generator network

The HVDC model shown in Figure 2 operates in a bidirectional manner. It consists of two voltage converter sections: the rectifier and the inverter. In rectification mode, the converter functions similarly to a conventional AC system, acting as a nonlinear load. In inversion mode, it aims to ensure system stability by synchronizing the voltage magnitude, phase angle, and frequency with the network, as illustrated in Figure 2(a). This synchronization is particularly vital for enhancing the voltage profile in weak or low-inertia AC networks, where voltage stability may be compromised by frequency fluctuations.

By modulating power exchange through the voltage source converter (VSC) in response to real-time frequency deviations, the converter maintains stable voltage levels, mitigating the risk of voltage sags or swells that could destabilize the system. This frequency-response control strategy is applicable in both rectification and inversion modes and plays a key role in improving the voltage profile in both conventional and VSC-based HVDC systems. In VSC HVDC systems, this control approach extends the capability to regulate voltage and provide frequency support even in "dead" AC networks-those lacking connection to a stable external grid. This dynamic adjustment enhances voltage stability, ensures reliable power delivery, and supports the integration of variable renewable energy sources into the grid. The equivalent circuit of the HVDC transmission system model is shown in Figure 2(b), which is used to perform the power flow analysis of the two converter stations as described below.



(a)

(b)

Figure 2. The systematic model of HVDC system, (a) two level converter section and (b) the equivalent circuit

The two stations connected at bus k to the station connected at bus m represent the rectifier and inverter stations with a detailed voltage representation at each bus. The active and reactive power injected at the rectifier station (bus k) are:

$$P_k = G_{VR1}\big(e_k^2 + f_k^2 - (e_{VR1} + f_{VR1})\big) + B_{VR1}(f_{VR1}e_k + e_{VR1}f_k) \tag{9}$$

$$Q_k = G_{VR1}(e_{VR1}f_k + f_{VR1}e_k) + B_{VR1}(-(e_k^2 + f_k^2) + e_{VR1}e_k + f_{VR1}f_k) \tag{10}$$

Similarly, the active and reactive power flow into the inverter station (bus m) are:

$$P_m = G_{VR2}\big(e_m^2 + f_m^2 - (e_{VR2} + f_{VR2})\big) + B_{VR2}(f_{VR2}e_m + e_{VR2}f_m) \tag{11}$$

$$Q_m = G_{VR2}(e_{VR2}f_2 + f_{VR2}e_m) + B_{VR2}(-(e_m^2 + f_m^2) + e_{VR2}e_m + f_{VR2}f_m) \tag{12}$$

Therefore, the total power into the HVDC system is as (13):

$$P_{HVDC} = P_{recf} + P_{inv} + P_{DC} \tag{13}$$

Where P_{HVDC} is the active power in the HVDC, P_{recf} is the active power in the rectifier and P_{inv} is the active power in inverter stations, respectively while the P_{DC} is the direct current (DC) link active power.

3.3. The topology of proportional integral controller operation in HVDC system

The PI controller model consists a proportional and integral gains, exogenous signal and firing angle. The inverter voltage and current of the HVDC controller introduce high-frequency dynamics that significantly impact both peak and light load conditions, as well as during large signal disturbances on the network. The system in Figure 3 compares the reference current I_{ref} with the measured DC current I_{dc} to determine the appropriate control action. The difference between these currents serves as the basis for adjusting the operation of the converter. This adjustment is implemented through the modulation of the thyristor firing angle. A power reference input (P_{ref}) and the measured power from the system are compared. The difference represents how much the actual power deviates from the desired set point. The proportional gain provides an immediate response proportional to the magnitude of the error while the integral gain integrates the error over time, ensuring that any persistent offset is driven to zero, hence correcting steady-state errors. The outputs of the proportional and integral gain are summed together, producing the control signal. This combined control signal determines the firing angle (α) for controlling converter operations. The firing angle α typically varies between 0° and 180°. When α = 0°, the converter operates at its maximum DC output voltage, maximizing the current flow. Conversely, when α =180°, the output voltage drops to zero, and no power is transferred. The PI controller is applied to swiftly and accurately regulate the converter firing angle, stabilizing the power flow and ensuring system reliability. It is applied in this like HVDC system for power system stability enhancement, and voltage control.

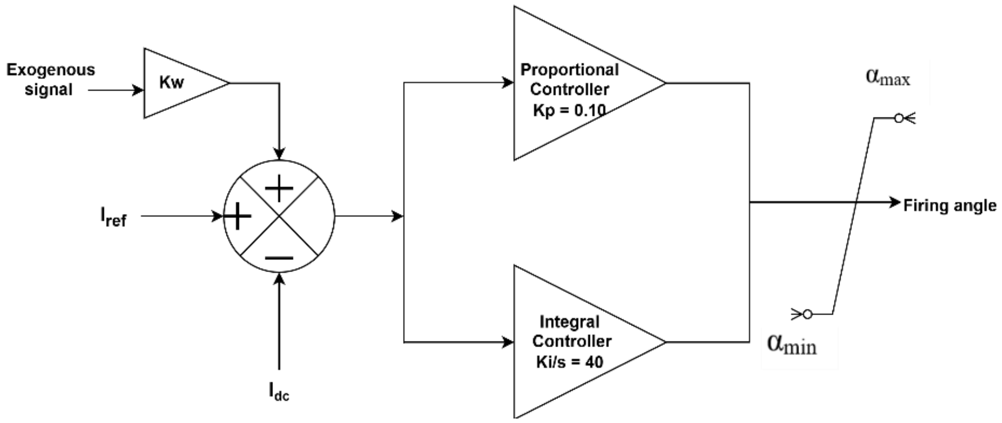


Figure 3. The controller diagram for the PI-Based HVDC system

4. RESULTS AND DISCUSSION

The result obtained from the power flow studies conducted on the test during the base case and the case of disturbance is highlighted in this section. When the network is subjected to a balanced three phase fault, a significant reduction in voltage magnitude at Akangba, Alagbon, Gombe, Gwagwalada, Kano, Olorunsogo, Omotosho, Onitsha and Geregu bus is observed. Theses bus had a voltage magnitude of 0.8024 p.u, 0.8242 p.u, 0.7457 p.u, 0.7973 p.u, 0.8678 p.u, 0.8267 p.u, 0.7638 p.u, 0.7732 p.u, 0.700 p.u. Their voltage magnitudes are below the statutory values of ±5% for the Nigeria transmission network and this forms the critical buses in the network. The detailed voltage profiles plot is shown in Figure 4.

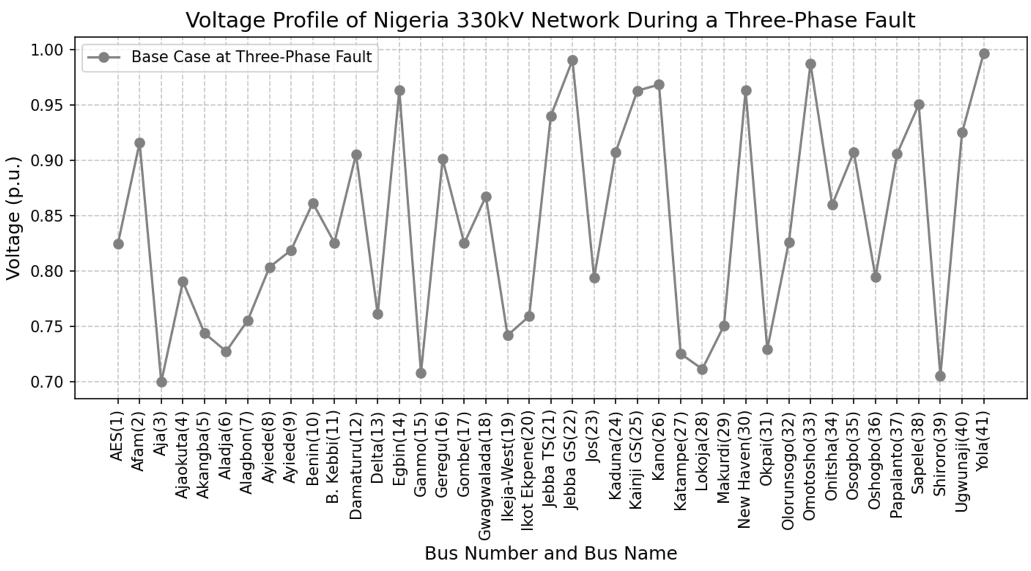


Figure 4. The voltage profile for the base case of the test network at three-phase fault

It is evident from the voltage profile that Gombe bus has the lowest voltage magnitude of 0.700 p.u. Eigenvalue analysis is conducted to determine the stability of the buses; it was observed that the Makurdi bus is the most unstable bus in the network with an eigenvalue of 3.3641±j5.2608 and a damping ratio of 0.0564. This becomes the candidate bus for the application of a balanced three phase fault. When a three phase is applied at bus 29, the conventional PI based HVDC system is connected along Makurdi to Jos transmission line the voltage profile is compared with the base case profile as shown in Figure 5.

The conventional PI-based HVDC system application on the test case network showed significant improvement in voltage stability, achieving a minimum bus voltage magnitude of 0.80 p.u. The HVDC system injects adequate reactive power into the network, demonstrating the effectiveness of the intelligent approach in improving voltage stability.

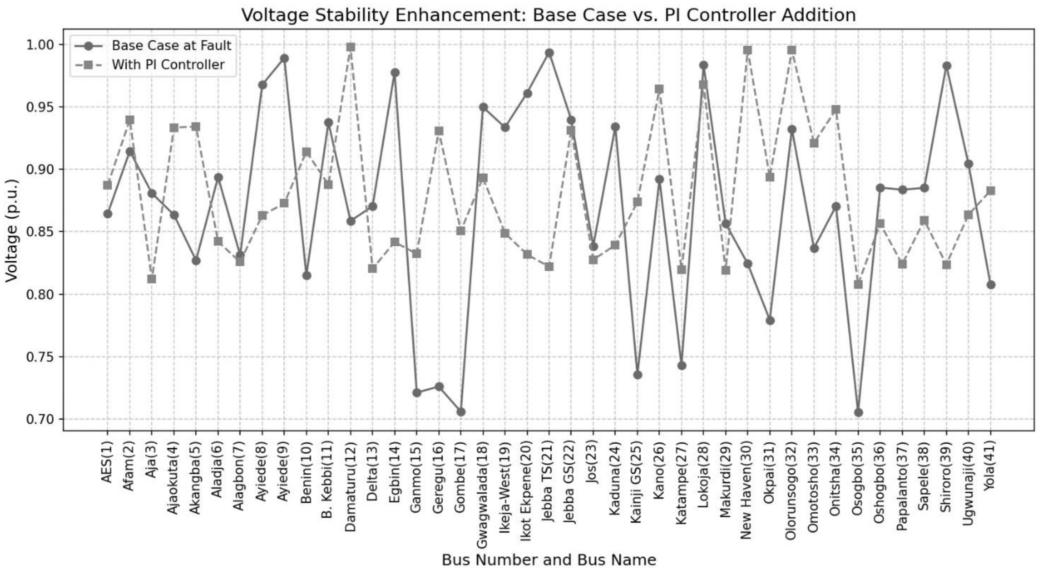


Figure 5. The Comparative assessment of the voltage profile between the base case and the improved case

5. CONCLUSION

In this research, the transmission network voltage profile is enhanced using an automated proportional integral based HVDC system. The power flow analysis is conducted using the Newton-Raphson power flow method, which is known for its robustness in modeling complex power systems. The PI-based HVDC system is designed and tuned analytically to optimize control and effectively respond to disturbances. The model is tuned on various scenarios to proportional and integral gain values and the best value is determined and implemented for maintaining stable voltage profiles, even during faults. The effectiveness of the proposed method is assessed by comparing voltage profiles during a balanced three-phase fault with and without the PI-based HVDC system. In the base case, the minimum voltage profile dropped to 0.70 p.u., indicating instability. With the proposed technique, the minimum voltage profile significantly improved to 0.80 p.u., highlighting its critical role in enhancing voltage stability. This substantial improvement demonstrates the method's potential for broader application in modern power systems. Future research could explore hybrid control systems and real-time testing to further enhance power grid stability and efficiency.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Uche C. Ogbuefi		✓				✓		✓	✓	✓	✓	✓		
Emenike Ejiogu	✓					✓			✓	✓		✓		✓
Tole Sutikno		✓			✓					✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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