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Power loss reduction and stability enhancement of power system through transmission network reconfiguration

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ABSTRACT

The power network faces several challenges as electricity usage rises, and the frequency of partial and total grid disruptions is of significant concern. This paper addresses the problem of voltage instability and high-power losses in transmission networks, which threaten the stability of the power grid. MATLAB R2023a/MATPOWER 5.0 is used to develop a model and analyse it using the Newton-Raphson load flow method. The analysis reveals a marginal voltage violation at Bus 13 (below 0.95 p.u.). To enhance stability and efficiency, the network was reconfigured using a hybrid whale algorithm and particle swarm optimisation (WAPSO) approach, incorporating new transmission lines (5-8 and 13-14) to improve connectivity and reduce congestion. The reconfiguration reduced active power losses by 29.5% (from 36.013 to 25.371 MW) and reactive power losses by 29.8% (from 301.30 to 211.59 MVAr). The system demonstrated first swing stability, with rotor angles remaining below π/2 (1.5669 rad maximum deviation) and fault clearance within the critical clearing time (0.2 s). Optimised exciter gains and a damping coefficient of 1.5 p.u. ensured effective oscillation suppression and stable generator voltages at 1.05 p.u. The hybrid WAPSO approach proved effective in optimising voltage and rotor angle stability, enabling the network to meet a 24.086 p.u. load demand while enhancing overall grid reliability.

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1. INTRODUCTION

The benefits of having a dependable electrical power network cannot be overstated in light of the rising electricity demand. Strengthening the topology of the power system and optimizing its operations are essential to reduce the likelihood of system breakdowns [1]. Restructuring the network is vital to ensuring resilience, stability, prosperity, and sustainability in the energy sector [2]. Stability is a critical factor in assessing the reliability of a power system during outages [3]. Power system stability is defined by the IEEE/CIGRE joint task force as "the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact" [4]. The goal is to ensure that it remains a focal point in electrical systems research. Enhancing the stability of the power system requires engineers, planners, and operators to consider rotor angle stability, short circuits, transient stability, and contingency planning. A thorough analysis of these elements is important for maintaining a balanced electricity supply and demand. The need for a redesigned grid system that is efficient, robust, and adaptive is paramount. Transmission network reconfiguration involves making necessary adjustments to power components within the network to enhance overall performance. This process may include fundamental evaluations such as load flow and fault analysis. By systematically reviewing and addressing these aspects, the grid infrastructure can achieve improved resilience and performance, ensuring an uninterrupted power supply and meeting consumer demands efficiently. Nigeria's power infrastructure faces several challenges as electricity usage increases.

The frequency of partial and total grid disruptions is of significant concern. This primarily results from the grid's outdated infrastructure, cascaded transmission line tripping due to overload, loss of synchronization among multiple network alternators, network topology, long-distance transmission lines, infrastructure deficiencies, over-voltages, vandalism, and protective device malfunctions [5]. As the grid expands to meet expanding demand and support the country's economy, more generators and transmission lines are added, complicating the system and increasing the risk of short circuits occurring and system collapse. To address these challenges, this study aims to investigate the optimal reconfiguration of the Western Nigerian 14-bus regional power network using hybrid whale algorithm and particle swarm optimization (WAPSO) techniques, focusing on power loss reduction, voltage profile improvement, and rotor angle stability assessment under various operating conditions. The Western Nigerian 14-bus regional power network is an essential component of the Nigerian national grid. Improving stability, efficiency, and dependability is important for encouraging economic growth and development, enhancing electricity quality, and guaranteeing system resilience. Optimizing regional networks will ensure the overall grid system's security and reliability.

Numerous studies have been undertaken to optimize network reconfiguration for improved stability and resilience. Study [6] proposed an improved brute-force method for optimizing the reconfiguration of extra-high voltage transmission networks. The goal was to reduce short circuits while still meeting steady-state and transient constraints. This cost-effective method identifies the optimal grid reconfiguration to reduce short circuits while meeting operational requirements. However, a key limitation of the study was its failure to adequately address rotor angle stability. This disadvantage was evident in the adjustments made to parameters such as generator exciter gain, voltage schedules, and dispatch strategies, without addressing critical clearing times or improving power oscillation stability in transmission lines and generators. In contrast, Naderipour *et al.* [7] explored optimal reconfiguration for unbalanced distribution systems aimed at loss reduction, improved power quality, and minimizing unserved energy using a fuzzy multi-criteria approach and an innovative enhanced coronavirus herd immunity optimizer. This method worked better than other methods when tested on IEEE 33 and 69-bus systems for both single-objective and multi-objective optimization. However, it did not include fault analysis or stability assessments. Similarly, Alanazi and Alanazi [8] applied an intelligent artificial electric field algorithm-pattern search to uneven IEEE 33-bus and real unbalanced 13-bus systems, focusing on loss reduction and voltage improvement. However, N-1 security constraints, short circuit analysis, and stability assessments were not addressed. Additionally, Cikan and Kekezoglu [3] examined equilibrium optimization and other meta-heuristic optimization techniques in a reconfigured distribution network with the sole purpose of real power loss reduction, improving the voltage level, and raising the reliability index. Nevertheless, N-1 security constraints, short circuit analysis, and stability analysis were not addressed. Several approaches addressed transmission network issues: Sikiru *et al.* [9] identified weak buses but neglected stability, while in [10], co-optimized energy and reserves without AC power flow are considered. Stability concerns were also overlooked in [11] and [12], which explored contingency-constrained optimal power flow.

Reconfiguring the network to increase system stability and reduce short circuits has been discussed in previous works including [13]–[19]. The concepts of bus splitting and line elimination was explored in [13]. Short circuit restriction was assessed in the study to minimize the fast voltage stability index's maximum value across all examined lines. Utilizing an altered IEEE 24-bus system, the work was evaluated. The objective of minimizing short circuit levels while also offering splitting reliable approaches was evaluated in [14]. This was done to restrict the splitting to the substations with the greatest short circuit currents alone and maintain a limited power flow in the splitting point. An IEEE 25-bus system and the Iraqi 400 kV power infrastructure were utilized for the inquiry. To solve the multi-objective function of N-1 contingency requirement and short circuit current limitation in the optimization issue, Doğan and Yörükeren [15] used a hybrid genetic algorithm (GA) and binary PSO to optimally determine the position for a bus architecture. However, the parameters of GA and binary PSO were not employed to optimize the topology of the transmission system in question. The importance of ideal bus splitting in resolving high short circuit current in a power system was covered in [16]. A meta-heuristic approach utilizing PSO and GA was employed. Compared to the GA, the PSO method proved to be more efficient. Nevertheless, N-1 contingency analysis and other forms of fault were overlooked by the authors. The Kuwait high voltage network's excessive short circuit current was addressed in [17] using a variety of strategies. Although dividing the current 275 kV network is the best way to address the rapidly rising short circuit levels, it is not clear where the splitting should be done. Two strategies for reducing voltage stability and short circuit violations were covered in [18]. The first approach uses a quick mathematical process to determine the change in the impedance matrix element. The second approach minimizes the short circuit capacity while taking bus voltage limits into account by using a linear programming methodology. The authors did not, however, take into account how the reconfiguration would affect the generators' rotor angle stability within the power system. To achieve short circuit restrictions while maintaining power flow constraints on bus bar switching, Van Acker *et al.* [19] showed how to employ a mixed integer non-convex quadratic constraint algorithm. While study [20] addressed transient stability issues by combining grid topology with machine learning techniques. The synchronous generators' rotor angle stability adjustments made to parameters such as generator exciter gain, voltage schedules, and dispatch strategies, without addressing critical clearing times or improving power oscillation stability in transmission lines and generators following a contingency were overlooked by the writers.

This study presents the application of a hybrid weighted aggregated particle swarm optimization (WAPSO) technique for the optimal reconfiguration of the Western Nigerian 14-bus regional power network. The primary objectives are to minimize active power losses, enhance voltage profiles, and improve rotor angle stability under fault and contingency conditions. The stability assessment focuses on tuning generator parameters—specifically exciter gain, voltage schedules, and power dispatch—without altering the critical clearing time (CCT). The proposed hybrid WAPSO-based reconfiguration strategy yields substantial improvements in network performance. Notably, the integration of two additional transmission lines (Line 5–8 and Line 13–14) enhances network connectivity, alleviates line congestion, and introduces alternative power flow paths, thereby increasing system reliability. The optimal reconfiguration results in a 29.5% reduction in active power losses across the regional grid.

Furthermore, the study demonstrates the effectiveness of hybrid WAPSO in optimizing generator control parameters. Exciter gains were tuned within the range of 50 to 250, voltage schedules were maintained between 0.95 and 1.05 p.u., and power dispatch levels were adjusted within generator operational limits. These adjustments led to improved transient and voltage stability, with significant reductions in rotor angle deviations. The system-maintained synchronism during fault scenarios, with rotor angle excursions remaining well below the critical $\pi/2$ threshold. Importantly, fault clearance times were preserved within the CCT, validating the robustness of the optimized configuration under severe disturbances. The remainder of this manuscript is organized as follows: Section 2 details the materials and methods employed, Section 3 presents the results and discusses their implications, and Section 4 concludes the study.

2. MATERIALS AND METHOD

This section explains a way of reconfiguring the Western Nigerian 14-bus regional grid network for stability enhancement. Utilizing MATLAB/MATPOWER environment and mathematical formulations, WAPSO and rotor stability were modelled. Newton Raphson's (NR) load flow method was applied to determine the steady-state solution. The examined network consists of 14 buses, incorporating four generators and 14 loads. All four generators are operational, collectively generating an active power of 2,444.3 MW and a reactive power of 866.2 MVAr. The data utilized in this study, comprising the single-line diagram, line data, bus data, generator data, and generator dynamic parameters, were sourced from the Transmission Company of Nigeria.

2.1. Newton Raphson load flow analysis

Load flow analysis was first applied to the network show in Figure 1 to determine the steady-state solution of the 14-bus Western Nigerian regional power system. The analysis provides an initial assessment of the power system, which is nonlinear due to the dynamic relationship between load, voltage magnitude, and circuit impedance. Since it is a non-linear problem, it must be solved iteratively. The method has a better convergence rate and high level of accuracy than other methods of load flow solution [21]. The equations of the Newton Raphson's load flow technique are stated below.

$$V_h = \frac{1}{Y_{hh}}\left[\frac{P_h - jQ_h}{V_h^*} - \sum_{\substack{f=1 \\ f\neq h}}^{n} Y_{hf}V_f\right] \quad (1)$$

The load flow formulation is given by the following sets of equations.

$$P_h = \sum_{\substack{f=1 \\ f\neq h}}^{n} |V_h||V_f||Y_{hf}|cos(\theta_{hf} - \delta_h + \delta_f) \quad (2)$$

$$Q_h = -\sum_{\substack{f=1 \\ f\neq h}}^{n} |V_h||V_f||Y_{hf}|sin(\theta_{hf} - \delta_h + \delta_f) \quad (3)$$

Equations (2) and (3) are sets of non-linear algebraic equations.

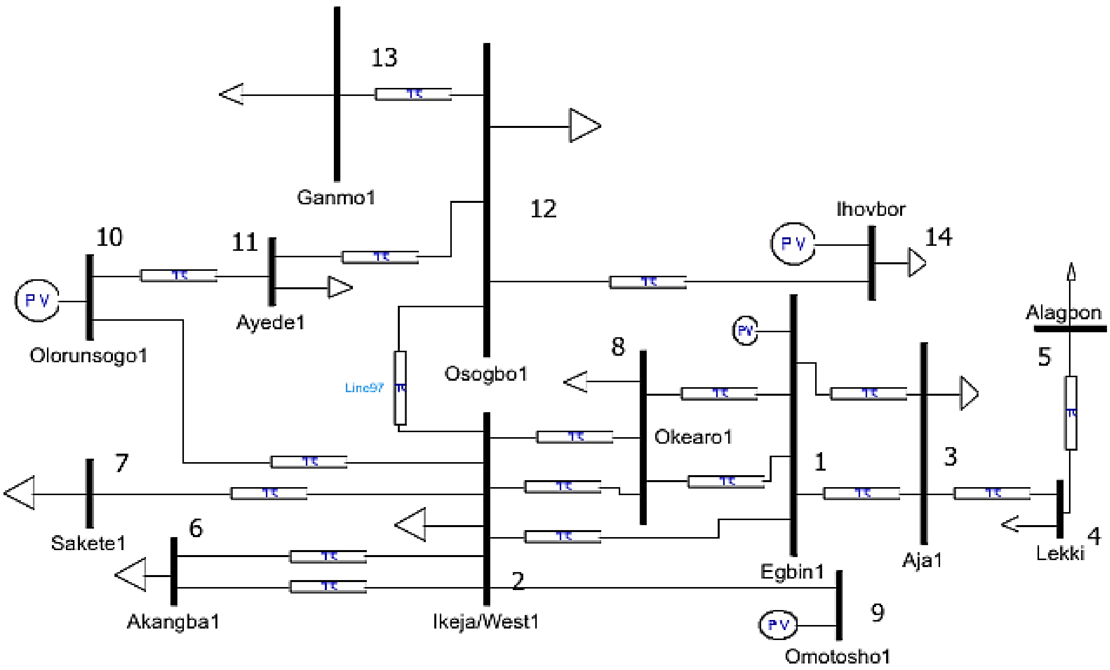

Figure 1. Single line diagram of the Western Nigerian regional grid network

2.2. Modelling of optimal network reconfiguration

The multi-objective function is stated considering power loss reduction and voltage profile improvement**.** The power loss of the network as expressed in [3] is given as:

$$\min P_{loss} = \sum_{h,f=1}^{N}\left(\frac{P_f^2+Q_f^2}{V_f^2}\right)R_{hf} \quad (4)$$

where P_{loss} is the power loss in the transmission line, $h \leftrightarrow f$ represents the bus number, and n denotes the number of transmission lines of the network, R_{hf} is the resistance of the line between h^{th} and f^{th} buses, P_f and Q_f are the real and reactive power values of bus-f^{th} and V_f represents the voltage magnitude of the bus. The active power loss reduction (ΔP_{loss}^{Dec}) is given as expressed in (5) by Cikan and Kekezoglu [3]:

$$\Delta P_{loss}^{Dec} = \frac{P_{loss}}{P_{loss}^{before}} \quad (5)$$

where, P_{loss} and P_{loss}^{before} are the power losses after and before network reconfiguration respectively. The voltage deviation (VD) index is given as expressed in [3]:

$$\min VD = \max\left(\frac{V_N - V_h}{V_N}\right) \ \forall_h = 1,2,3,\dots n \quad (6)$$

where, V_N and V_h are the nominal and bus voltages respectively. The goal is to reduce the voltage variation as it approaches zero. This improves the network's voltage profile. The fitness function is the combination of (5) and (6) with the weighted function to form a single objective function.

$$Fitness\ Function = \min\left(\Delta P_{loss}^{Dec} * W_r + VD * W_v\right) \tag{7}$$

where, W_r and W_v represent the weight coefficients of the objective function and their summation should amount to 1.

The objective function is subject to the following constraints:

a. Voltage limit: Power systems network has voltage level and it is given by its tolerance boundaries.

$$V(min) \leq V_h \leq V(max) \tag{8}$$

where, V_h is the voltage magnitude at bus h. for the Nigerian grid network, the tolerance is $\pm 5\%$. That is $0.95\ (bus) \leq V_h \leq 1.05(bus)$ at network bus.

b. Active power and reactive power limits: These are the equality constraints of the network. Absolute power limit: The limit is given as

$$S_h < S_{max} \tag{9}$$

where, S_h is the transmission line flow at h and S_{max} is the permissible maximum power flow.

c. Line current limit: the line current must not exceed its thermal permissible limits (I_h^{max}) and Ω_l is the set of the network transmission line [22].

$$|I_h| \leq I_h^{max} \qquad \forall_h \in \Omega_l \tag{10}$$

2.3. Rotor angles stability problem formulation

The goal is to minimize the rotor angle deviation. The starting state of a synchronous generator is used as the benchmark value. The deviation value is calculated by deducting the difference at the start of the fault state from the difference at the end. The magnitude of rotor angle variation is calculated by squaring the cumulative difference [23].

$$\min \sum_{h \in S_G, t \in T} (\delta_{h,t} - \delta_{h,0})^2 \tag{11}$$

where $\delta_{h,t}$ denotes the rotor angle; S_G represents the number of generators; T stands for all times except the starting point at $t = 0, meaning\ T = t_{during} \cup t_{after}$. This is subject to the following constraints as given [23], [16]: Bus load balance limit: The load balance equations are given as (12) and (13).

$$P_{G,h}^i - P_{D,h}^i = \sum_{f=1}^{n} |V_h^i|\,|V_f^i||Y_{hf}^i| \cos\left(\theta_{hf}^i - \delta_h^i + \delta_f^i\right) \tag{12}$$

$$Q_{G,h}^i - Q_{D,h}^i = \sum_{f=1}^{n} |V_h^i|\,|V_f^i||Y_{hf}^i| \cos\left(\delta_h^i - \delta_f^i - \theta_{hf}^i\right) \tag{13}$$

where $P_{G,h}$ and $Q_{G,h}$ are the real and reactive power output respectively; $P_{D,h}$ and $Q_{D,h}$ are the real and reactive load; the superscript i of the parameters stands for the initial state. Let $h \in S_n$, S_n is the number of the entire buses. The power outputs of the generator during and after fault occurrence are expressed in (12) and (13). The output power of each generator is given as (14).

$$P_{elect} = E_h^2 Y_{hh} cos\theta_{hh} + \sum_{\substack{h=1 \\ h \neq f}}^{m} |E_h||E_f||Y_{hf}| \cos\left(\theta_{hf} - \delta_h + \delta_f\right) \tag{14}$$

The swing equation of a synchronous generation is given as shown in [24]:

$$\frac{2H}{\omega_s}\frac{\partial^2 \delta}{\partial t^2} = P_{mech} - P_{elect} - \frac{D_k}{\omega_s}\frac{\partial \delta}{\partial t} \tag{15}$$

where D_k is the damping coefficient in per unit and δ is the angle of the synchronous generator.
By using the per unit value of $\bar{t}$ in (15) above yields.

$$2H\omega_s \frac{\partial^2 \delta}{\partial \bar{t}^2} = P_{mech} - P_{elect} - D_k \frac{\partial \delta}{\partial \bar{t}} \quad (16)$$

Therefore, $\bar{J} = 2H\omega_s = 4\pi f H$ is the per unit moment of inertia. The inertia constant H, which shapes the turbine-generator's dynamic characteristics, is a critical generator parameter. The moment of inertia represents the influence of the combined spinning masses of the turbine and generator as stated in [25]. Hence, the swing equation for damping becomes.

$$2H\omega_s \frac{\partial^2 \delta}{\partial \bar{t}^2} = P_{mech} - P_{Loss} - P_{elect} - D_k \frac{\partial \delta}{\partial \bar{t}} \quad (17)$$

During fault condition, the swing equation is given as (18).

$$2H\omega_s \frac{\partial^2 \delta}{\partial \bar{t}^2} + D_k \frac{\partial \delta}{\partial \bar{t}} = P_{mech} - P_{Loss} - P_{elect(during\ fault)} \quad (18)$$

After fault condition, the swing equation is express as (19).

$$2H\omega_s \frac{\partial^2 \delta}{\partial \bar{t}^2} + D_k \frac{\partial \delta}{\partial \bar{t}} = P_{mech} - P_{Loss} - P_{elect(after\ fault)} \quad (19)$$

Generator voltage schedule equations: the expression is given as (20) and (21).

$$T_f \frac{\partial R_f}{\partial t} = -R_f + \frac{K_f}{T_f} E_X \quad (20)$$

$$T_a \frac{\partial V_R}{\partial t} = -V_R + K_a\left(V_{ref} - V_t\right) - \frac{K_a K_f}{T_f} E_X + K_a R_f \quad (21)$$

Generator exciter's gain equation: The exciter equation is given as expressed in (22).

$$T_e \frac{\partial E_X}{\partial t} = V_R - [K_e + SE(E_X)]E_X \quad (22)$$

Generator dispatch equation: This is given in (23).

$$F_{GD} = \sum_{i=1}^{l} C_i(P_{Gi}) \quad (23)$$

The critical clearing angle and time equations: Are expressed in the equations expressed in (24) and (25).

$$\delta_{cr} = cos^{-1}[(\pi - 2\delta_0)sin\delta_0 - cos\delta_0] \quad (24)$$

$$t_{cr} = \sqrt{\frac{2H\delta_{cr} - \delta_0}{\pi f P_{mech}}} \quad (25)$$

where, δ_{cr} and t_{cr} represent the critical clearing angle and critical clearing time respectively.

2.4. Modelling of the hybrid WAPSO model

The hybrid method's distinctive feature is the WOA's capacity to compensate for the PSO's limitations. Because of its constant inertia weight, the PSO suffers from a constraint in particle search space for tackling complicated engineering problems. Figure 2 shows the hybrid WAPSO technique flowchart. The hybrid WAPSO method uses the following equations to update velocity and location as illustrated in (26) and (27) [26]:

$$V_i(t+1) = \omega . V_i(t) + C_1 r_1 \left(\overrightarrow{X_{SA}}(t+1) - X_i(t)\right) + C_2 r_2 \left(g_{best}(t) - X_i(t)\right) \quad (26)$$

$$X_i(t+1) = X_i(t) + V_i(t+1) \quad (27)$$

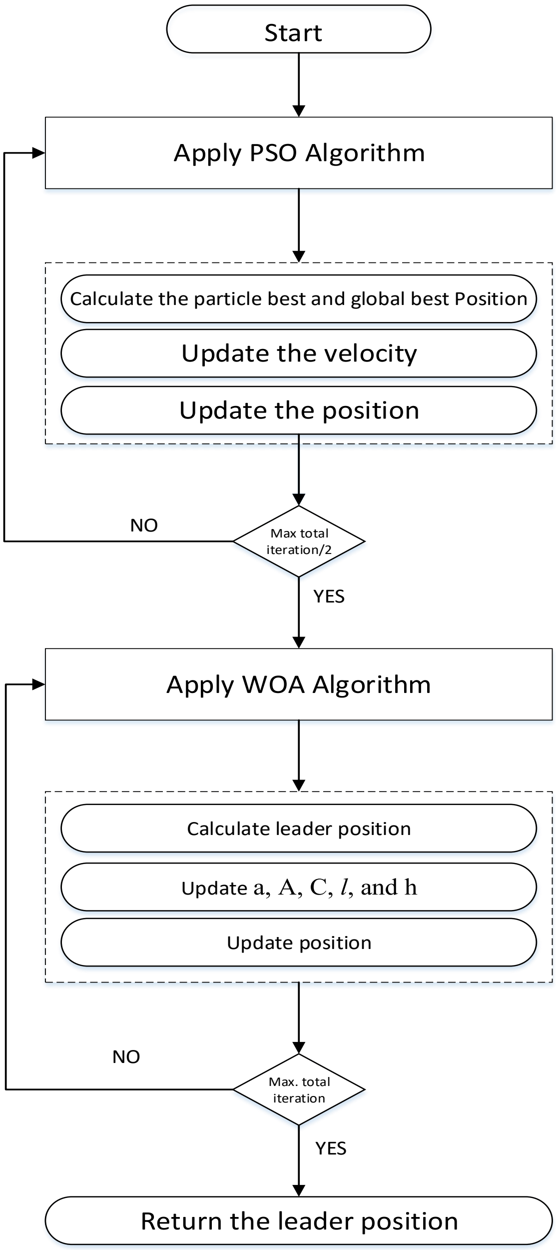

Figure 2. Hybrid WAPSO technique flowchart [27]

3. RESULTS AND DISCUSSION

The NR power flow analysis demonstrated rapid convergence, achieving a solution in just four iterations within a time span of 0.01 seconds. This swift convergence highlights the computational efficiency of the NR method, recognized for its quadratic convergence rate when applied to well-conditioned systems with appropriately chosen initial estimates as confirmed by [21]. The voltage profile of the network, depicted in Table 1, shows that the minimum and maximum voltage magnitudes are 0.942 pu (at Bus 13) and 1.000 pu. (at Bus 1), respectively. Although the voltage levels generally fall within the acceptable operational range of 0.95 to 1.05 pu., the voltage at Bus 13 is marginally below the lower limit, indicating a potential area of vulnerability that requires targeted interventions, such as network reconfiguration or reactive power compensation, to maintain stability. The voltage angle ranges from -3.43° (Bus 7) to 23.74° (Bus 14), with a significant angle difference observed on Line 12-14, suggesting substantial power transfer stress, highlighting the need for network reconfiguration. This observation may indicate the necessity for voltage support or reactive power compensation to maintain system stability. The system experiences total active and reactive power losses of 36.01 MW and 301.30 MVAr, respectively.

Table 1. Load flow analysis of the 330kV, 14-Bus Western Nigerian grid network

Bus Number	Voltage		Generation		Load	
	Mag (pu)	Ang (pu)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	1.000	0.000	1242.210	587.590	216.500	100.000
2	0.985	-1.245	0.000	0.000	574.600	250.000
3	0.992	-0.901	0.000	0.000	102.800	40.000
4	0.984	-1.579	0.000	0.000	81.200	35.000
5	0.985	-1.579	0.000	0.000	198.500	80.000
6	0.975	-2.494	0.000	0.000	461.300	150.000
7	0.971	-3.431	0.000	0.000	175.900	50.000
8	0.992	-0.661	0.000	0.000	27.100	10.000
9	1.000	4.573	225.500	-6.260	18.000	7.000
10	1.000	0.905	360.600	194.360	9.000	3.000
11	0.977	0.560	0.000	0.000	166.900	70.000
12	0.956	3.351	0.000	0.000	202.300	100.000
13	0.942	1.525	0.000	0.000	111.100	45.000
14	1.000	23.739	616.000	90.460	63.100	25.000

3.1. Network reconfiguration of the Western Nigerian 14-bus power network

The results present the impact of optimal network reconfiguration using hybrid WAPSO on the power network's voltage profile and power losses of the Western Nigeria 14-bus power network. The reconfiguration was achieved by strategically adding new transmission lines to improve system stability and reduce transmission losses as indicated in Figure 3. The hybrid WAPSO algorithm uses the fitness function from (10) to evaluate possible transmission line setups. It randomly selects indices within the population of candidate transmission line configurations while maintaining a diverse set of possible additions. The algorithm ensures that the buses selected for interconnection comply with the configuration constraints of the power network. By integrating WOA's robust global exploration with the PSO technique's local search capabilities, WAPSO achieves a balance between discovering possible additional line configurations and fine-tuning their implementation. The newly added transmission lines specifically include Line 5-8 (connecting Alangbo to Okearo) and Line 13-14 (connecting Ganmo to Ihovbor). These additional connections aim to strengthen network connectivity, minimize line congestion, and provide alternative power paths, thereby enhancing system reliability. By expanding interconnections, the network achieves improved load distribution, reducing the likelihood of localized overloading and voltage instability.

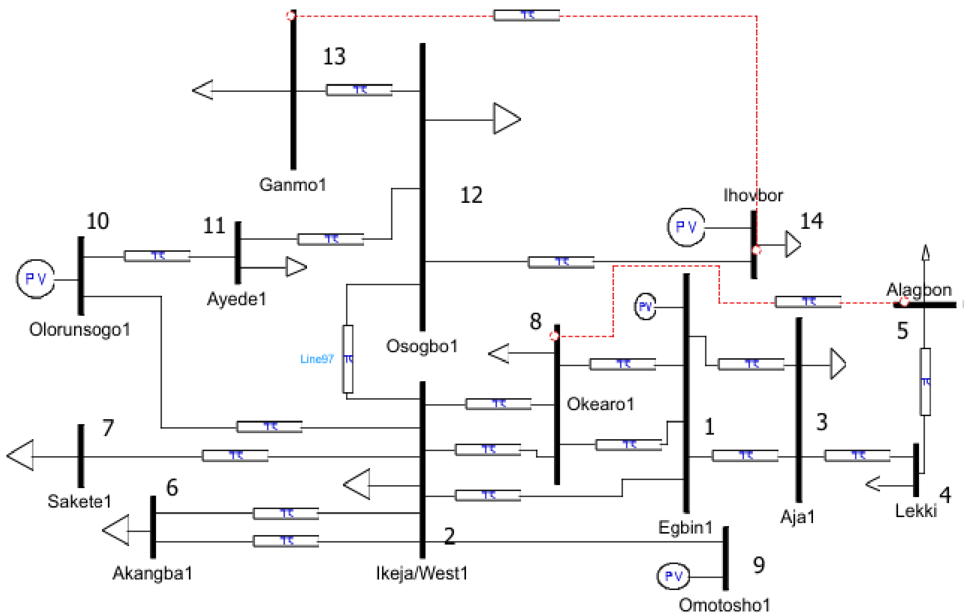

Figure 3. Single line diagram of the reconfigured Western 14-bus system

After reconfiguration, the minimum voltage rose to 0.972 p.u. at Sakete, while the maximum remained at 1.000 p.u.. The increase in minimum voltage suggests improved voltage stability, reduced voltage drops, and enhanced reactive power support. Significant improvement was noticed at Ganmo (Bus 13) where voltage increased from 0.942 to 0.985 p.u., indicating substantial stability enhancement due to the added line to Ihovbor. Also, at Osogbo (Bus 12) where the voltage improved from 0.956 to 0.983 p.u., highlighting enhanced support from the optimized network configuration. At Ayede (Bus 11), notable voltage improvement was recorded from 0.977 to 0.987 p.u., showcasing better reactive power management. These voltage improvements suggest effective mitigation of low-voltage conditions, enhanced load-sharing and better reactive power distribution across the network. The majority of the buses-maintained voltage levels close to the nominal value of 1.0 p.u., signifying a more stable and balanced system as depicted in Figure 4.

Both the active and reactive power was reduced significantly. The active power losses decreased from 36.013 to 25.371 MW, representing approximately 29.5% of the active power loss reduction, and the reactive power losses reduced from 301.30 to 211.59 MVAr, a reduction of about 29.8%. These reductions indicate enhanced transmission efficiency, reduced I^2R losses, and improved network stability. The minimized reactive power losses demonstrate better voltage regulation and reactive power support. The optimized network configuration effectively redistributes power flows, reduces line overloading, and minimizes resistive losses, contributing to overall improved operational efficiency, as shown in Figure 5. The addition of transmission lines addressed line congestion and improved load distribution, aligning with existing literature emphasizing optimal network reconfiguration for loss minimization and voltage profile enhancement [3], [5], and [7]. The use of WAPSO to optimize line additions demonstrates a novel approach to achieving these improvements, offering a model for other regional grids.

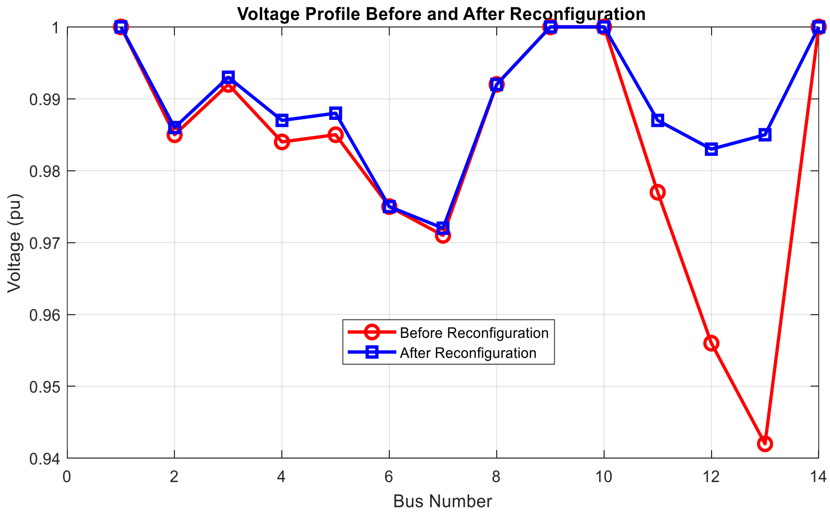

Figure 4. Voltage profile before and after the Western Nigerian 14-bus network reconfiguration

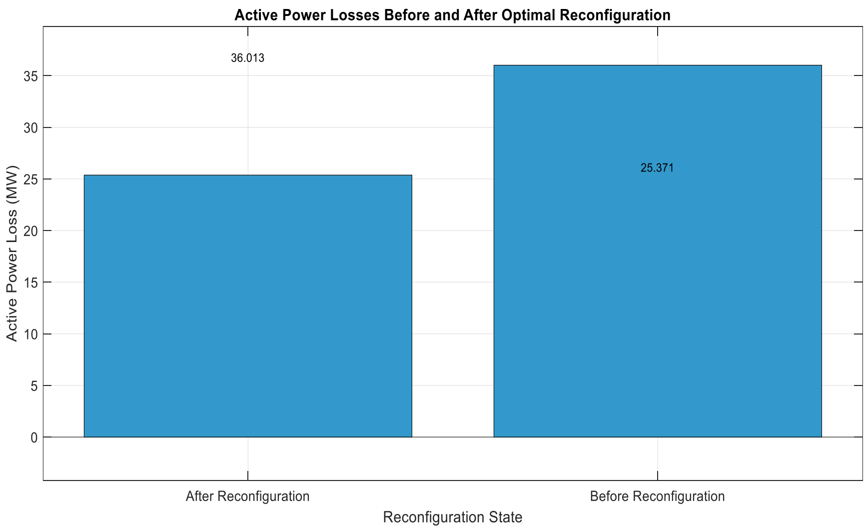

Figure 5. Active power losses of the Western Nigerian power system after reconfiguration

3.2. Rotor angle stability optimization for the 14-bus Western power network

The rotor angle stability optimization results for the 14-bus Western Nigerian power network, as presented in Table 2, confirm a stable system under the hybrid WAPSO approach. The optimization focused on improving rotor angle stability by fine-tuning three key parameters for each generator including exciter gain (K_{exc}), voltage schedule ($V_{schedule}$), and power dispatch ($P_{dispatch}$). The study was conducted on the 14-bus system, which includes four generators located at buses 1, 9, 10, and 14, with a total load demand of 24.086 p.u. The optimization successfully met this demand with an exact dispatch match of 24.086 p.u. The maximum rotor angle deviation recorded was 1.5669 rad, slightly below the stability threshold of π/2 (approximately 1.57 rad), confirming that the system remains stable and making the results tangible and measurable.

Table 2. Optimized parameters for rotor angle stability of the 14-bus network

Bus No.	K_{exc}	$V_{schedule}$ (pu)	$P_{dispatch}$	Final Delta (rad)
1	250	1.05	10.847	1.5669
9	50	1.05	3.350	0.7222
10	250	1.05	5.750	1.2064
14	250	1.05	4.139	1.5654

The exciter gain values for buses 1, 9, 10, and 14 were set at 250, 50, 250, and 250, respectively. Notably, buses 1, 10, and 14 reached the upper limit of the assumed optimization range (50-250). High exciter gains enhance the responsiveness of the automatic voltage regulator (AVR) by increasing the field voltage (E_{fd}) to maintain terminal voltage near the scheduled value ($V_{schedule}$). However, excessive gains can lead to over-excitation, potentially causing significant rotor angle swings or even instability. Bus 9, on the other hand, had a much lower K_{exc} of 50, the lowest allowable value, suggesting that a lower exciter gain at this location helps dampen oscillations. This is due to its lower inertia (H=4) and its power dispatch being at the maximum allowable limit (3.35 pu). The high exciter gain values at buses 1, 10, and 14 indicate a need for strong voltage support, driven by their substantial power dispatches (10.847, 5.75, and 4.139 pu, respectively). However, the uniform application of the upper limit suggests that the optimization process may have been constrained, potentially overlooking more optimal intermediate values. The optimization balanced transient stability with steady-state performance, though the uniform voltage schedule and high exciter gains at most buses suggest potential over-excitation risks. The lower K_{exc} at Bus 9 effectively dampened oscillations, leveraging its lower inertia. These findings align with the swing equation dynamics ((4)-(6), (18)-(19)) and critical clearing time (25), providing robust framework for transient stability analysis. The variation in exciter gain values across the generators demonstrates the optimizer's attempt to balance damping efforts effectively.

The voltage schedule was uniformly set at 1.050 pu across all buses, reaching the upper limit of the optimization range (0.95 to 1.05 pu). This value maximizes voltage support, which in turn enhances synchronizing torque and improves transient stability by increasing electrical power output (P_{elect}). However, setting all voltage schedules at the maximum may result in over-voltages in certain areas of the network, potentially stressing equipment or leading to voltage instability if reactive power limits are exceeded. The uniformity of $V_{schedule}$ suggests that the optimizer prioritized maximizing synchronizing torque for all generators.

The total power dispatch exactly matched the target load demand of 24.086 pu, satisfying the power balance constraint. Buses 9 and 10 were fully utilized, operating at their maximum limits (3.35 pu and 5.75 pu, respectively), while Bus 1 was near its limit (10.847 pu out of 13.2 pu). In contrast, Bus 14 operated significantly below its capacity (4.139 pu out of 8.5 pu). The dispatch distribution was uneven, with Bus 1 shouldering the largest share (45% of the total dispatch), followed by Bus 10 (24%), Bus 14 (17%), and Bus 9 (14%). The heavy reliance on Bus 1, which has a high inertia (H=6.5), suggests that the optimization strategy leveraged its stability to manage a significant portion of the load. The fact that Buses 9 and 10 reached their maximum limits implies that the system is constrained by their capacities, potentially limiting its ability to accommodate additional contingencies. Meanwhile, Bus 14, which operated well below its capacity, could have been utilized more efficiently to balance the load distribution. It is likely that the optimizer reduced Bus 14's dispatch to minimize rotor angle swings, as its lower inertia (H=1.37) makes it more susceptible to oscillations.

Table 2 further highlights that the maximum rotor angle deviation was 1.5669 rad at Bus 1, just below the stability threshold of π/2. This confirms that the system maintains synchronism since rotor angles exceeding π/2 typically lead to loss of stability as confirmed in [20]. Bus 9 exhibited the smallest deviation (0.7222 rad), likely due to its low exciter gain and full utilization of its capacity, which minimized its contribution to oscillations. In contrast, Buses 1 and 14 were close to the stability limit, suggesting that they are the most critical generators in the system. Their high exciter gains and substantial power dispatches likely contributed to their larger rotor angle deviations. With buses 1 and 14 operating near the stability threshold, the system is on the edge of stability, requiring careful monitoring. Small disturbances or inaccuracies in the model could push these generators beyond the stability limit, leading to potential instability. The lower rotor angle deviation at Bus 9 suggests that the optimizer effectively dampened oscillations at this generator, likely due to its low K_{exc} and full dispatch utilization. Conversely, the higher rotor angles at buses 1 and 14 may have been influenced by their high inertia and dispatch levels, as well as network topology factors, such as the fault at Bus 4 and the contingency involving the outage of line 1-3, which could have disproportionately impacted these generators.

In this setting, rotor angle deviation serves as the primary indicator of transient stability. The fact that the maximum deviation remains just below the threshold confirms that the system can withstand the specified fault (at Bus 4 with a 0.1-second duration) and contingency (line 1-3 outage) without losing synchronism. Additionally, the power balance criterion, which ensures that the total dispatch precisely meets the load demand, is crucial for steady-state operation. The optimizer's ability to satisfy this constraint with minimal error highlights its effectiveness in maintaining system stability and operational integrity.

Figure 6 presents the dynamic response of the 14-bus Western Nigerian power system following the optimization of rotor angle stability. The figure consists of three subplots, illustrating rotor angles (δ in radians), rotor speed deviations (Δω in rad/s), and generator voltages (V in p.u.) over a 2-second simulation period. This system includes four generators positioned at buses 1, 9, 10, and 14, which experience a fault at Bus 4 lasting 0.1 seconds, along with a contingency on the 1-3 transmission line. As a multi-machine power system, the 14-bus network undergoes optimization using a hybrid WAPSO approach. This method fine-tunes exciter gains (K_{exc}), voltage schedules ($V_{schedule}$), and power dispatches ($P_{dispatch}$) to enhance rotor angle stability under fault conditions. The optimized parameters from previous results include exciter gains of 250.00 at buses 1, 10, and 14, while Bus 9 has a lower value of 50.00. The voltage schedule remains uniform at 1.050 pu across all buses, and the power dispatch values are set at 10.847 pu (Bus 1), 3.350 pu (Bus 9), 5.750 pu (Bus 10), and 4.139 pu (Bus 14). The final rotor angle deviations settle at 1.5669 rad (Bus 1), 0.7222 rad (Bus 9), 1.2064 rad (Bus 10), and 1.5654 rad (Bus 14). Stability analysis confirms that the system remains stable, as the maximum rotor angle deviation of 1.5669 rad remains just below the critical threshold of π/2 (approximately 1.57 rad).

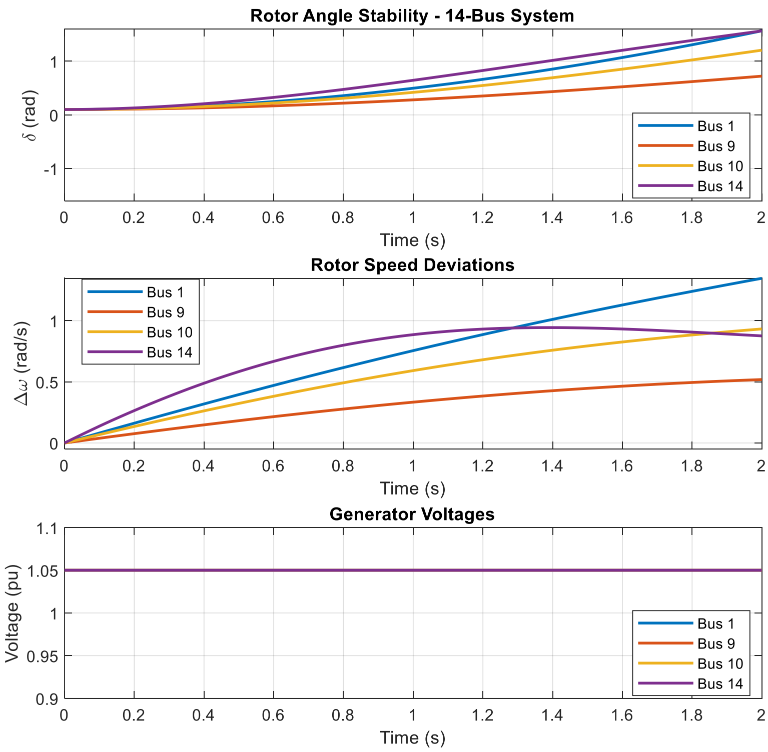

Figure 6. Rotor angle stability optimization of the 14-bus Western Nigerian network

The simulation captures the transient response over two seconds, with the fault occurring at t=0 and being cleared at t=0.1 s, followed by the line 1-3 outage. The subplots reveal insights into the system's transient stability, damping behaviour, and voltage regulation. The rotor angles, shown in the top subplot, rise sharply during the fault (t=0 to 0.1 s) due to an imbalance between mechanical power input (P_{Mech}) and electrical power output (P_{elect}), as described by the swing equation. The fault at Bus 4 increases system impedance, reducing P_{elect} and accelerating the rotor angles. Once the fault is cleared at t=0.1 s, the rotor angles continue rising due to the kinetic energy accumulated, peaking around t=0.2 to 0.3 s. The peak values align with the final rotor angle deviations, with Bus 1 reaching 1.5669 rad, Bus 9 at 0.7222 rad, Bus 10 at 1.2064 rad, and Bus 14 at 1.5654 rad. The angles then stabilize without further oscillations, confirming a well-damped response.

The system exhibits first swing stability, as none of the rotor angles exceed π/2, ensuring generator synchronization. The fault duration (0.1 s) remains within the critical clearing time (CCT=0.2 s), allowing system recovery without loss of synchronism. Effective damping is evident from the absence of oscillatory behaviour post-fault, attributed to the increased damping coefficient (D=1.5 pu) and optimized exciter gains. Notably, Bus 9, with the lowest exciter gain (50.00), experiences the smallest rotor angle deviation, indicating that a reduced K_{exc} at this location helps suppress oscillations. Throughout the simulation, all generators sustain a stable voltage of 1.05 pu, consistent with the optimized voltage schedule. The absence of fluctuations suggests that the exciter model successfully regulates voltage, ensuring stability across the system.

4. CONCLUSION

This research investigates the reconfiguration of the Western Nigeria's regional grid transmission network to enhance the stability of the power grid. The study was conducted using a MATLAB R2023a/MATPOWER 5.0 simulation environment, focusing on the Western 14-bus, 330kV grid network. The single-line diagram was modelled using PSAT version 2.1.11, while steady-state analysis was performed using the NR load flow method. The result indicates that only one bus was outside of the statutory level of ±5% of 330 kV (0.95-1.05 p.u). Although the voltage levels generally fall within the acceptable operational range of 0.95 to 1.05 p.u., the voltage at Bus 13 is marginally below the lower limit, indicating a potential area of vulnerability. The network was subsequently reconfigured to enhance voltage stability and reduce power losses. Optimal network reconfiguration using the hybrid WAPSO approach led to significant improvements, including the addition of transmission lines 5-8 (Alangbo to Okearo) and 13-14 (Ganmo to Ihovbor). The load distribution was optimized, lowering active power losses from 36.013 to 25.371 MW (a 29.5% reduction) and reactive power losses from 301.30 to 211.59 MVAr (a 29.8% reduction). The system exhibits first swing stability, as none of the rotor angles exceed π/2, ensuring generator synchronization. The fault duration (0.1 s) remains within the critical clearing time (CCT=0.2 s), allowing system recovery without loss of synchronism. Effective damping was evident from the absence of oscillatory behaviour post-fault and optimized exciter gains. Notably, Bus 9, with the lowest exciter gain (50.00), experiences the smallest rotor angle deviation, indicating that a reduced K_{exc} at this location helps suppress oscillations. Throughout the simulation, all generators sustain a stable voltage of 1.05 pu, consistent with the optimized voltage schedule. The absence of fluctuations suggests that the exciter model successfully regulates voltage, ensuring stability across the system. The analysis confirmed that the Western 14-bus network, the system successfully met the total load demand of 24.086 pu, with a maximum rotor angle deviation of 1.5669 rad, slightly below the stability threshold of π/2 (1.57 rad). This research validates the effectiveness of a hybrid WAPSO approach in optimizing rotor angle stability and reducing power losses in the Western Nigerian 14-bus regional power network, demonstrating its potential for improving power grid stability and efficiency. Subsequent research should prioritize the exploration of alternative optimization methodologies and the incorporation of renewable energy sources into the 14-bus power system. The proposed strategy enhances grid stability in developing regions like Sub-Saharan Africa, promoting economic and social progress. It integrates steady-state and transient stability optimization, laying the groundwork for future grid designs.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
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E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

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

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