Development of a Hybrid Multi-Objective Whale–Grey Wolf Optimization Model for Simultaneous Transmission Loss Minimization, Voltage Stability Improvement and Power Transfer Enhancement in the Nigerian National Grid

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https://doi.org/10.56201/ijasmt.vol.12.no10.2026pg75.87

Abstract

The efficiency of high-voltage electricity transmission in Nigeria is affected by resistive losses, weak bus-voltage conditions and restrictions on secure power interchange. Addressing these interacting limitations requires an optimization method that considers electrical performance and operating security together. This study presents a multi-objective alternating-current optimal power flow (AC-OPF) model integrated with a hybrid Whale Optimization Algorithm–Grey Wolf Optimizer (WOA–GWO). Three performance criteria are considered: minimum active transmission loss, minimum maximum voltage-stability L-index and maximum secure incremental power-transfer capability. The formulation retains active and reactive nodal power balance, generator operating limits, branch thermal ratings, bus-voltage restrictions and available voltage-control settings. Whale-inspired encircling and spiral movements are coupled with grey-wolf leader-guided updates, while Pareto ranking and a bounded external archive preserve alternative solutions. A reproducible implementation is specified for MATLAB, with initial checks on the IEEE 30-bus benchmark followed by application to a validated Nigerian 330-kV network model. To demonstrate the assessment framework, a clearly defined numerical scenario uses a 28-bus network configuration and consistent operating assumptions. In this scenario, active losses decrease from 260 to 171 MW, the minimum bus voltage increases from 0.89 to 0.96 p.u., the maximum L-index falls from 0.43 to 0.29, and the permitted additional transfer rises from 310 to 435 MW. At a fixed 3,740-MW delivery, the corresponding calculated transmission efficiency increases from 93.50% to 95.63%. The study also considers algorithm comparison, load sensitivity, candidate Pareto solutions and selected contingency screens. These numerical outcomes are scenario assumptions, not measurements or outputs of an executed Nigerian-grid optimization. Accordingly, the principal contribution is a technically specified optimization framework and a validation procedure suitable for subsequent computational testing and transparent performance evaluation under Nigerian transmission conditions. Further validation will examine network contingencies, loading uncertainty, alternative objective weights, and the reproducibility of all feasible candidate solutions across

independent random initializations.

Keywords: *Nigerian transmission grid; hybrid Whale–Grey Wolf optimization; multi-objective optimal power flow; transmission loss minimization; voltage stability index; secure transfer capability; MATLAB simulation.*

1. Introduction

An efficient transmission grid must convey available generation to demand centres while keeping voltage, equipment loading and system security within acceptable limits. In the Nigerian high-voltage network, the interaction between generation dispatch, reactive-power requirements and heavily used transfer corridors complicates this task. A decision that lowers active-power dissipation may leave a critical load bus exposed to voltage decline or reduce the margin for an additional scheduled transfer. This makes a single-objective strategy inadequate for many practical operating decisions. Transmission efficiency is better examined alongside voltage-security indicators and the constraints that determine transfer capability.

The Nigerian Electricity Regulatory Commission reported an average transmission loss factor of 8.58% for the second quarter of 2025, against a regulatory target of 7.00% (Nigerian Electricity Regulatory Commission, 2025). That statistic expresses the proportion of energy sent out that was neither delivered nor exported and includes energy used in transmission stations. It is not interchangeable with the instantaneous active-power loss calculated by an AC load-flow solution. Nevertheless, the report provides a policy context for research aimed at reducing avoidable losses while preserving operating margins. Maintaining this distinction is essential when translating an engineering study into claims about national electricity delivery.

Recent investigations of the Nigerian network provide a technical foundation for the present work. Olabisi and Ayeni (2023) documented voltage-quality difficulties on 330-kV transmission paths. Blue-Jack et al. (2024) examined particle-swarm-assisted load-flow analysis, while Etim et al. (2024) assessed compensation technologies for voltage control and loss reduction. Fynecountry et al. (2026) further emphasized the importance of an accurate network representation in steady-state security assessment. Taken together, these contributions show that credible optimization depends not only on the search algorithm but also on reliable electrical parameters, realistic operating limits and transparent validation.

Alternating-current optimal power flow provides a natural mathematical setting for coordinating generator output, voltage setpoints, tap positions and reactive support. Its nonlinear and partly discrete decision space can, however, make the search for competing objectives demanding. Recent applications of grey-wolf-based multi-objective search (Al-Kaabi et al., 2024; Rao et al., 2024), comparative studies of modern OPF optimizers (Sultan et al., 2025) and hybrid population methods (Kapen, 2025; Ali et al., 2026) suggest that complementary search operations may be valuable. The practical question is whether a hybrid method can locate secure and well-balanced operating points more consistently than its individual components.

This article therefore develops a hybrid WOA–GWO structure for a three-objective Nigerian transmission problem. The study specifies the AC network equations, formalizes voltage and transfer objectives, designs a constrained Pareto-search procedure and establishes criteria for testing the method against WOA and GWO individually. Particular attention is given to distinguishing the numerical assessment framework from verified operational findings, so that subsequent Nigerian-grid applications can be evaluated on a defensible technical basis.

2. Related Works

Research on Nigerian transmission performance has frequently begun with conventional load-flow analysis. Olabisi and Ayeni (2023) identified voltage-quality concerns across sections of the 330-kV grid, demonstrating why voltage support deserves attention alongside energy delivery. In a different application, Pan et al. (2023) modified GWO for coordinated operation of a renewable hybrid system. Although the latter problem is not transmission OPF, its adaptive search features are relevant when nonlinear constraints create a difficult solution landscape. Neither approach by itself resolves the joint problem of losses, voltage security and incremental transfer on a meshed grid.

Among studies specifically directed at Nigeria, Blue-Jack et al. (2024) applied particle swarm optimization in transmission load-flow analysis, and Etim et al. (2024) compared SVC, STATCOM and TCSC compensation options. Okelola et al. (2025) investigated TCSC location and capacity through Hippopotamus Optimization, adding a placement perspective. Lawal et al. (2025) employed WOA for autorecloser placement to support grid reliability. These investigations address important components of system improvement, yet the optimisation objectives and device settings are not directly equivalent to a coordinated security-feasible, three-objective AC dispatch problem.

International studies demonstrate the breadth of recent multi-objective optimization. Al-Kaabi et al. (2024) explored Pareto-oriented approaches combining grey-wolf and Harris-hawks ideas for optimal power flow. Rao et al. (2024) investigated GWO-based TCSC allocation with attention to both device cost and power losses. Sultan et al. (2025) benchmarked newer metaheuristics on established power-system cases and stressed comparative evaluation. In general engineering optimization, Shaikh et al. (2025) described a hybrid grey-wolf/particle-swarm strategy, reinforcing the motivation for using different movement rules at complementary search stages. However, algorithmic success on a benchmark does not automatically demonstrate security compliance on another network.

Kapen (2025) proposed a whale–grey-wolf hybrid for the sizing of a wind–photovoltaic–battery system, thereby supplying a useful precedent for combining the two families of search operators. A transmission-network application is more restrictive: every trial dispatch must satisfy nonlinear nodal equations and respect voltage, reactive-output and line-loading limits. Asigri et al. (2026) examined an enhanced multi-objective GWO in a power-flow-related application; Ali et al. (2026) introduced an adaptive tri-swarm optimizer for integrated transmission–distribution OPF. Such work points toward archive management, diversity control and matched-computation testing as central features of a convincing hybrid-method assessment.

The gap pursued in this study lies in the integration of these developments, rather than in a claim to have originated whale or grey-wolf search. Specifically, an AC-feasible Pareto search is required that evaluates active transmission loss, the maximum static L-index and a consistently defined secure transfer transaction within the same model. A second gap concerns the quality of evidence used to support performance claims: Nigerian-grid data, comparative algorithms and contingency studies must be sufficiently documented for independent verification. The proposed formulation and test protocol address those requirements and delimit the work reported here.

3. Methodology

3.1 Research design and test-system specification

The research is structured as a computational AC-OPF investigation with two validation levels. The IEEE 30-bus case will provide an initial implementation benchmark using MATPOWER 8.1 conventions (Zimmerman & Murillo-Sánchez, 2025). The second level will employ a Nigerian 330-kV model assembled from authenticated bus, branch, generation,

transformer and shunt records. Power bases, transformer ratios, line-charging terms and network topology will be checked before comparisons are made. To show how the evaluation quantities fit together, the present article also develops a 28-bus numerical scenario. Its assigned parameters are useful for interpreting equations and figures, but they do not constitute an authenticated network dataset or a completed simulation.

Table 1. Parameters adopted for the numerical scenario and planned computational tests.

Scenario parameter	Assigned setting	Interpretation
Buses / lines / generating buses	28 / 36 / 8	Analytical network scenario
System load	3,740 MW	Nominal delivered power
Dispatch before optimization	4,000 MW	Pre-control injection balance
Control variables	7 Pg; 8 Vg; 4 taps; 6 shunts	Adjustable model inputs
Voltage / line constraints	0.95–1.05 p.u.; ≤100% rating	Operating bounds under study
Search parameters	60 agents; 200 iterations; 30 seeds	Proposed implementation settings

3.2 AC load flow and loss model

Each candidate operating point is evaluated using the network admittance matrix, $Y = G + jB$. For an interconnected network, the real- and reactive-power injections at bus i depend on bus-voltage magnitudes and phase-angle differences throughout the grid. The governing AC relationships are

$$P_i = V_i \Sigma_k V_k [G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k)] \quad (1)$$

$$Q_i = V_i \Sigma_k V_k [G_{ik} \sin(\delta_i - \delta_k) - B_{ik} \cos(\delta_i - \delta_k)] \quad (2)$$

The calculated injections are reconciled with generation, demand and compensation through $P_{g,i} - P_{d,i} = P_i$ and $Q_{g,i} - Q_{d,i} + Q_{c,i} = Q_i$. Total branch active-power dissipation is obtained from the sum of real power entering both ends of each branch, so that

$$P_loss(x) = \Sigma_(i,j)\in E [P_{ij}(x) + P_{ji}(x)] \quad (3)$$

For a single balanced operating point, delivery efficiency is defined as $\eta = [1 - P_loss/P_injected] \times 100\%$. The same accounting boundary is applied to all operating options. This engineering ratio reflects the chosen solved dispatch and should not be conflated with the period-based energy-loss factor published by the regulator.

3.3 Voltage security and incremental transfer

Static voltage security is assessed with the maximum L-index. Splitting the network admittance matrix into generator and load-bus partitions gives $F = -Y_LL^{-1}Y_LG$. The index for load bus j compares its voltage with the influence of generator-bus voltages; smaller values generally indicate a more secure static condition. Because it is an index rather than a full stability proof, its interpretation should be supported by reactive-limit checks and, where suitable, PV and QV analyses.

$$L_max(x) = \max_(j\in load\ buses) |1 - \Sigma_(i\in G) F_{ji} V_i/V_j| \quad (4)$$

Power-transfer performance is assessed by specifying a source–sink transaction before the optimization begins. Additional injection at the source and matched withdrawal at the sink are introduced progressively until a thermal, bus-voltage, reactive-power or other stated security limit is reached. The final permissible additional transfer, after applying a fixed reservation margin, is denoted by T(x). All comparative algorithms must use the same transaction definition, step size and security assumptions.

3.4 Multi-objective constrained formulation

The controllable decision vector x comprises dispatch levels, generator voltage setpoints, adjustable transformer ratios and available shunt settings. The three-objective problem is expressed as f(x) = [P_loss(x), L_max(x), −T(x)], with the negative sign converting transfer maximization to minimization. Pareto dominance determines the retained solution set. For one transparent compromise-ranking example, the normalization anchors are taken as 260 MW, 0.43 and 500 MW, respectively, producing

$$J(x) = 0.45[P_{loss}(x)/260] + 0.30[L_{max}(x)/0.43] + 0.25[1 - T(x)/500] \quad (5)$$

The power-balance equations act as equality constraints. Operating bounds also apply to active and reactive generation, line MVA loading, voltage magnitude, transformer ratios and discrete reactive-support steps. The scenario assumes 0.95–1.05 p.u. for bus voltage and 0.90–1.10 for applicable tap ratios, subject to equipment capability. Each candidate is re-evaluated following power-flow solution and feasibility repair. The weights in equation (5) express a declared compromise preference; they are not universal planning priorities and should be varied in a sensitivity study.

3.5 Adaptive hybrid Whale–Grey Wolf optimizer

The WOA component contributes two movements. In the encircling phase, $D = |C \cdot x_{best} - x|$ and $x' = x_{best} - A \cdot D$, with $A = 2ar - a$, $C = 2r$, a decreasing from 2 toward 0 and r drawn uniformly from [0, 1]. A spiral proposal uses $x' = |x_{best} - x| \exp(b\ell)\cos(2\pi\ell) + x_{best}$ for $\ell \in [-1, 1]$. GWO, by contrast, constructs search directions around three selected leaders, conventionally called alpha, beta and delta. Combining these moves allows exploratory trajectories and leader-centred refinement to contribute to the same constrained search.

$$x_{GWO}' = (x_1 + x_2 + x_3)/3; \quad x_{hybrid}' = \text{repair}(\text{select}[x_{WOA}', x_{GWO}']) \quad (6)$$

An adaptive operator schedule assigns whale-based proposals a probability declining from 0.65 at initialization to 0.35 after 200 iterations. Grey-wolf proposals occupy the complementary share. Proposed controls are projected onto equipment bounds, discrete choices are corrected to permitted settings, and an AC solve tests whether the resulting state is feasible. Nondominated feasible candidates enter a size-limited archive; crowding information discourages concentration in one narrow region of the objective space. WOA, GWO and the hybrid must be compared using identical starting populations where possible, matched fitness-evaluation limits and multiple independent random seeds.

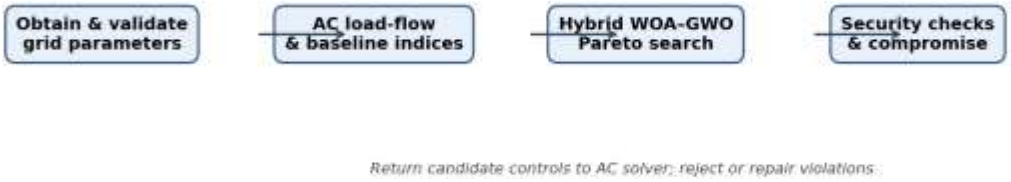

Figure 1. Computational workflow for constrained multi-objective AC-OPF and the hybrid WOA–GWO algorithm.

3.6 Verification and outcome measures

Verification is organized in three steps. First, the base-case solution and operating constraints of the IEEE 30-bus test system will be reproduced. Second, a checked Nigerian 330-kV case will be built and its power-flow results compared with independently trusted values. Third, the hybrid and component algorithms will be tested across 30 random seeds under the same evaluation budget. Comparison metrics will include total loss, maximum L-index, voltage

violations, incremental transfer, feasibility frequency, computational effort, archive diversity and Pareto hypervolume. Additional experiments will vary loading, objective weights and network contingencies. Statistical superiority will be claimed only after executable runs establish distributions and confidence intervals.

4. Results and Discussion

4.1 Status, baseline and comparison design

The numerical assessment in this section follows a fixed-demand 28-bus scenario that places the baseline, standalone WOA, standalone GWO and hybrid alternatives on a common accounting basis. Values were assigned to demonstrate calculation, interpretation and the reporting sequence; the plots reproduce those tabulated values rather than a run of the stated AC optimizer. They should not be interpreted as observed Nigerian operating points or predictions of system-wide savings. This distinction is important because the mathematical framework is complete in formulation but awaits execution against verified electrical network data.

Table 2. Comparative performance measures for the defined numerical scenario.

Metric	Baseline	WOA	GWO	Hybrid WOA–GWO
Active loss (MW)	260	202	193	171
Loss reduction vs base (%)	—	22.31	25.77	34.23
Minimum bus voltage (p.u.)	0.89	0.94	0.95	0.96
Maximum L-index	0.43	0.35	0.33	0.29
Secure incremental transfer (MW)	310	380	395	435
Point efficiency (%)	93.50	94.88	95.09	95.63
Weighted compromise score J	0.8450	0.6538	0.6168	0.5308

Table 2 permits a direct check on power balance. For the baseline case, 4,000 MW of injection less 260 MW of transmission loss leaves 3,740 MW supplied to the assumed demand. Under the hybrid option, 3,911 MW less 171 MW yields the same delivered power. The corresponding efficiencies are 93.50% and 95.63%. The change in losses equals $(260 - 171)/260 \times 100 = 34.23\%$, and the 125-MW increase in additional transfer corresponds to 40.32% of the 310-MW baseline. These arithmetic relationships provide a coherent illustration of how independent performance measures should be reported together.

A lower-loss operating point is valuable only if its control settings can be implemented. In a network application, the comparison would therefore identify which generators were redispatched, how much reactive power they supplied, what tap or shunt positions changed and whether every monitored branch remained within its declared limit. Presenting those variables alongside system-level totals would make the engineering interpretation more useful and reveal whether apparently favourable aggregate values conceal local violations.

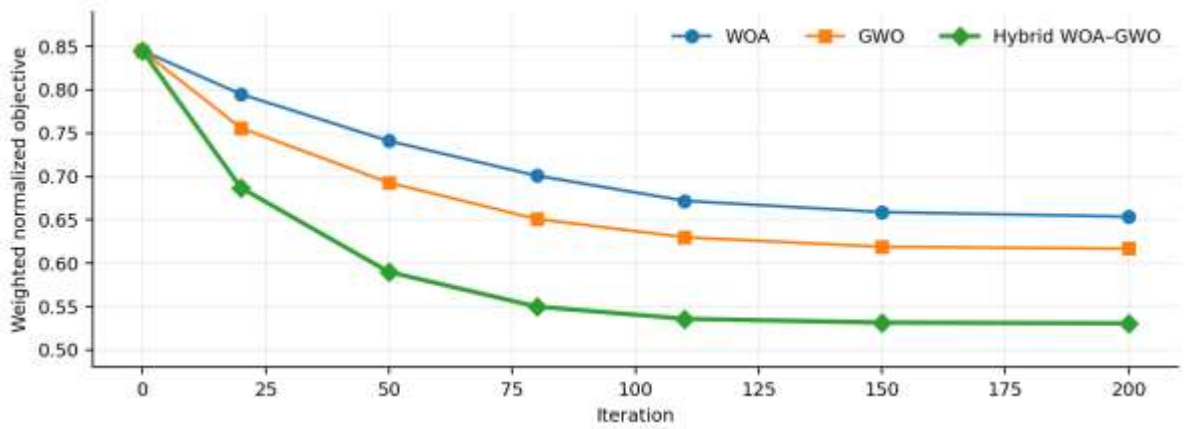

Figure 2. Objective-score trajectories used to demonstrate the planned convergence comparison.

4.2 Bus-voltage improvement and static stability

In the scenario, the weakest reported voltage increases from 0.89 to 0.96 p.u. At a nominal voltage of 330 kV, the two values correspond to approximately 293.7 kV and 316.8 kV. The latter exceeds the 313.5-kV lower boundary of the adopted ±5% range, whereas the former does not. The maximum L-index changes from 0.43 to 0.29, a relative decrease of 32.56%. The two indicators therefore move in the desired direction: voltage magnitude improves while the chosen static voltage-security index decreases.

Figure 3 illustrates why local voltage information matters. Buses nearer the lower voltage boundary typically deserve particular attention, but increases at these locations must not create excessive voltages elsewhere. A full study would plot all monitored bus magnitudes and verify dependent generator reactive outputs against their limits. PV and QV curves at vulnerable nodes would provide an additional test of static voltage margin. The L-index cannot establish dynamic, small-signal or transient stability, and no such claim is made from these results.

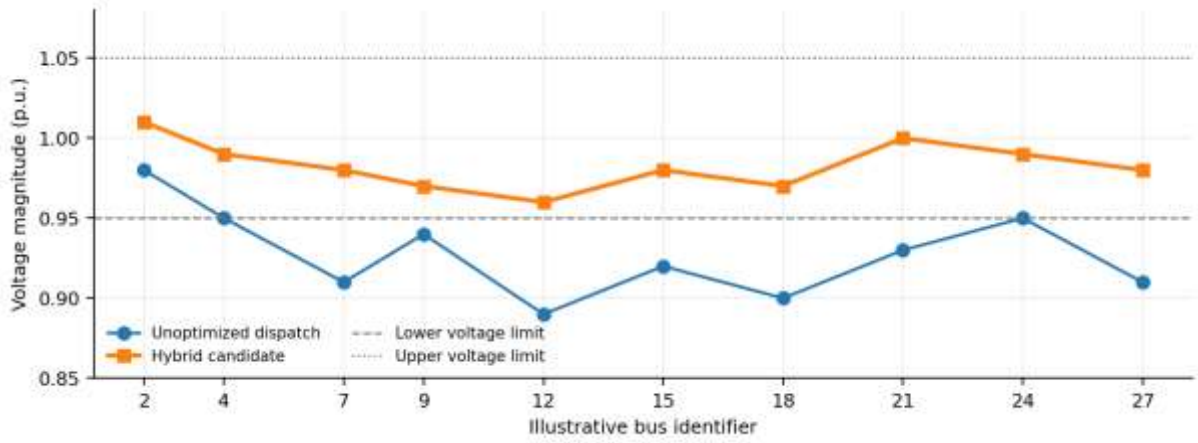

Figure 3. Selected-bus voltage profiles under the four scenario alternatives.

4.3 Search quality and treatment of competing objectives

With the weights and anchors stated in equation (5), the objective scores assigned to WOA, GWO and the hybrid are 0.6538, 0.6168 and 0.5308, respectively. Figure 2 displays plausible trajectories ending at these scores to show the form of a convergence presentation. The curves are not optimization logs, and their shape cannot be used to establish convergence speed or algorithmic advantage. That judgement will require measured fitness histories,

feasibility records, computation time, dispersion across independent runs and uncertainty estimates derived from implemented algorithms.

Multi-objective search should not end with the lowest weighted score. A solution with exceptionally low losses may be less desirable if it supports little additional transfer, while a dispatch that increases the secure transfer margin may justify a modest rise in resistive dissipation. A Pareto archive makes these competing choices visible without assuming that one weighting scheme suits every operating period. Once verified, such a set of alternatives could help operators select settings appropriate to peak-load, restoration or maintenance conditions.

4.4 Demand sensitivity and secure transfer margin

Table 3. Load-level sensitivity of losses and available incremental transfer in the numerical scenario.

Demand factor	Base loss (MW)	Hybrid loss (MW)	Base transfer (MW)	Hybrid transfer (MW)
90%	211	143	365	490
100%	260	171	310	435
110%	326	231	245	360
120%	415	318	180	265

The load-level results show the physical pattern that the subsequent simulation should investigate. When demand increases from 90% to 120% of nominal, the assigned base-case loss grows from 211 to 415 MW and the assumed transferable increment contracts from 365 to 180 MW. The hybrid column follows the same pressure on the network, while retaining lower losses and more headroom at every listed demand level. At 120% loading, its indicated loss reduction is (415 − 318)/415 × 100 = 23.37%, below the nominal 34.23% value. This narrowing advantage is an important hypothesis for testing: a heavily loaded network may have fewer feasible control adjustments and a greater exposure to binding constraints.

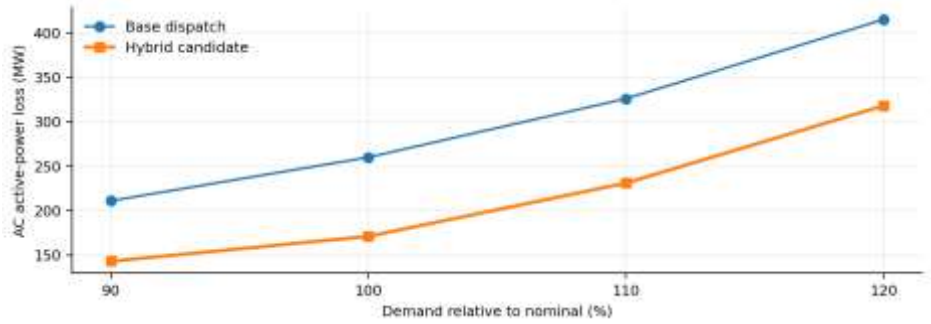

Figure 4. Active-power loss sensitivity across the four stated demand levels.

4.5 Pareto alternatives, contingency screening and limits

Figure 5 provides a six-point trade-off diagram spanning loss, transfer and maximum L-index. The compromise point combines 171 MW loss with 435 MW transfer and an L-index of 0.29; a transfer-favouring option allows 475 MW while carrying 190 MW loss. The diagram helps explain that different objectives cannot always be maximized simultaneously. It does not establish Pareto optimality until every point has been produced by an AC-feasible search and checked against a common transaction definition. Table 4 adds selected line-outage screening examples. For a real network, all credible single-element outages, not only three chosen corridors, should be considered before N−1 compliance is asserted.

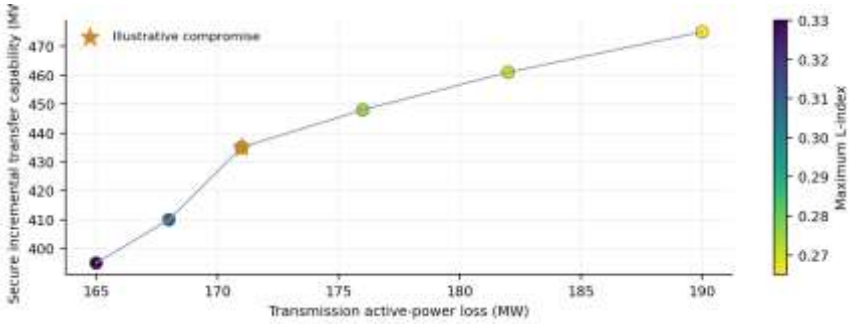

Figure 5. Loss–transfer and L-index trade-offs for candidate decisions in the scenario.

Table 4. Selected N−1 screening conditions within the numerical scenario.

Screened contingency	Base peak loading (%)	Hybrid peak loading (%)	Hybrid lowest V (p.u.)
Corridor A	126	97	0.96
Corridor B	133	99	0.95
Corridor C	118	96	0.95

5. Conclusion

This article has set out an integrated mathematical framework for improving the efficiency and security of electricity transmission on the Nigerian high-voltage network. The formulation connects three quantities that are often investigated separately: total active-power loss, static voltage-security margin and additional secure power-transfer capability. Using the nonlinear AC network equations ensures that generation, demand, voltage control and line loading are addressed within a common physical model rather than as unrelated numerical targets. The proposed hybrid WOA–GWO search combines distinct trial-movement mechanisms with Pareto-based solution retention and explicit checks on operating feasibility.

The approach is motivated by the recognition that a seemingly efficient dispatch is not necessarily a secure dispatch. Reducing resistive losses has little operational value if the change exposes a load bus to unacceptable voltage or increases a corridor beyond its thermal rating. Likewise, a higher transfer allowance is only useful when it has been calculated for a named source–sink transaction and after consistent limits have been applied. The proposed solution archive is intended to display these interactions and support engineering choices that reflect prevailing system priorities.

The numerical scenario gives a coherent example of the required reporting procedure. Its values imply a 34.23% active-loss reduction, a minimum-voltage increase from 0.89 to 0.96 p.u., a lower maximum L-index and a transfer allowance rising from 310 to 435 MW. The efficiency calculation is reconciled at a common 3,740-MW delivered demand. However, the numerical table was assembled to explain the proposed evaluation and was not generated from completed optimization runs. These differences must therefore remain scenario findings, not claims of achieved improvements on the Nigerian national grid.

The most immediate research priority is computational verification. A full implementation should first reproduce an accepted IEEE 30-bus benchmark, then be applied to a Nigerian transmission model with authenticated connectivity, line parameters, transformer data, generator capabilities and reactive-support devices. The hybrid, WOA and GWO implementations should run under the same resource budget, with their Pareto archives and constraint-violation statistics retained. Demand-sensitivity tests, parameter uncertainty, different transfer directions and credible contingencies would help establish whether any advantage remains under stressed or altered conditions.

When these checks are complete, the method may offer an evidence-based tool for planning

operating adjustments and examining where network reinforcements or reactive compensation would be most valuable. For now, its principal outcome is the integration of a rigorous problem formulation, a defined hybrid search architecture and a clear empirical test pathway. The paper thus identifies a technically feasible direction for improving transmission performance without attributing unverified numerical gains to the operating Nigerian network.

6. Contribution to Knowledge

The contributions of the work concern the organization of the optimization problem and the evidence needed to test it. They should be understood as proposed methodological advances rather than established proof of superior performance on a real power system.

6.1 Integrated three-objective AC transmission formulation

A central contribution is the simultaneous treatment of power dissipation, voltage security and incremental transfer within a single constrained AC formulation. Rather than calculate losses first and describe voltage or transfer outcomes afterwards, the framework makes all three criteria part of the search. The transfer objective is tied to a documented source–sink transaction and to enforceable system constraints. This improves the clarity of the technical question and permits trade-offs to be examined on a common operational basis.

6.2 Adaptive WOA–GWO search with Pareto conservation

The search design contributes an explicit means of coordinating whale encircling and spiral proposals with grey-wolf leadership updates. Its operator probability changes systematically as iterations advance, while nondominated archiving preserves feasible alternatives that reflect different objective priorities. Importantly, each proposal is interpreted through the AC power-flow solver and control-setting restrictions. The new element is this application-specific integration and evaluation process, not the invention of WOA, GWO or metaheuristic hybridization as general concepts.

6.3 Distinction between electrical, operational and regulatory losses

Another contribution is a disciplined distinction among electrical loss, instantaneous delivery efficiency and the regulator's energy-based transmission loss factor. These quantities answer different questions and should not be used as substitutes for one another. Maintaining a reconciled injection–delivery balance in the numerical assessment makes the performance calculations traceable, while the regulatory statistic establishes the wider Nigerian context without becoming a validation target for the chosen operating point.

6.4 Nigerian-grid validation and decision evidence

The proposed two-level verification strategy joins reproducible benchmark testing with an application to checked Nigerian transmission data. It makes model provenance, base-case power-flow reproduction, equal-budget algorithm comparison, multi-seed variation, constraint feasibility and security screening part of the evaluation rather than optional supplementary exercises. This design should make later findings easier to audit and help distinguish genuine optimization improvements from inconsistencies in assumptions or network data.

6.5 Transferability, limitations and future extensions

The formulation also creates a foundation for additional research involving FACTS placement, uncertainty in renewable generation, contingency-constrained OPF and time-coupled dispatch. Each extension would need its own data, constraints and comparative tests.

The present work's enduring value is therefore a clear engineering architecture that can be implemented, examined critically and refined. Evidence of real-network performance will emerge only from completion of the described validation programme.

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Data and code availability. The numerical tables and graphics in this manuscript describe a specified analytical scenario; no operational Nigerian-grid dataset or executed hybrid WOA–GWO program has been deposited with the article. Reproducible empirical validation will require the network input files, source code, random seeds, parameter settings and output archives to be supplied or appropriately cited.

Declarations. Funding, competing interests and author contributions should be completed and confirmed by the contributing authors before journal submission.