



Real Power-Loss Minimization in the Nigerian 54-Bus Transmission Network: Data Integrity, AC-OPF Formulation and Reproducibility Requirements

Zakka Barnabas^{*1}, Chimen Sabo Jamous^{*2}

^{*1}Technical Education Department, Electrical/Electronic Section, Kaduna State College of Education, Gidan Waya Kaduna State, Nigeria (jovidor@gmail.com)

^{*2}Department of Electrical/Electronic Engineering, Abubakar Tafawa Balewa University Bauchi, Nigeria. (csabotoro@gmail.com)

ABSTRACT

Real power loss remains a major concern in the Nigerian high-voltage network because every megawatt dissipated in transmission must be supplied by additional generation and may therefore increase operating cost and emissions. This paper develops a reproducibility-centered framework for studying real power-loss minimization on a Nigerian 54-bus, 330-kV research representation extracted from a broader multi-objective optimal power-flow study. Rather than reporting an unsupported optimization gain, the paper audits the electrical data required before a defensible loss-minimization experiment can be conducted. The supplied case contains 54 buses, comprising one reference bus, eleven additional generator-controlled buses and forty-two load buses. Summation of the bus schedule gives 6,501.9 MW and 3,922.0 MVar of listed demand, while the specified non-slack active generation is 4,537.0 MW. The line schedule comprises 80 branch records distributed across 62 unique bus-pair corridors and forms a connected topology. However, verified branch thermal ratings, non-unity taps settings, phase shifts, shunt/reactor controls, definitive generator capability limits and a validated mapping between twenty-one thermal-station objective records and twelve generator-connected buses are not yet available. These gaps prevent a new AC loss figure from being reported responsibly. The paper therefore formalizes the Newton-Raphson and AC optimal power-flow requirements for loss evaluation, contrasts the case with published Nigerian 54-bus studies, and identifies a minimum reproducibility package for future loss optimization. The central finding is methodological: loss reduction claims for Nigerian test systems are meaningful only when the exact network version, base case, branch flows, control settings, feasibility limits and absolute MW loss are reported together.

Keywords: active power loss; Nigerian 54-bus system; AC optimal power flow; MATPOWER; Newton-Raphson; transmission network; reproducibility; data validation

1. Introduction

Transmission losses are inseparable from the physical operation of an alternating-current power system. Real power is dissipated in branch resistance as current flows between generating stations and load centers, and the amount of loss changes with the pattern of generation, bus-voltage magnitudes, voltage angles, reactive-power circulation and network-control settings. In a system with limited generation reserves and persistent network constraints, reducing avoidable loss is not merely an efficiency exercise. It changes the quantity of generation required to serve a fixed demand and may influence both operating expenditure and environmental performance.

The Nigerian transmission literature contains numerous studies on load flow, voltage weakness, reactive compensation, FACTS placement and loss reduction, but the network representation is not uniform. Published cases include 28-, 31-, 52-, 54-, 56- and 58-bus models, sometimes with different equipment counts even when the nominal bus count is the same. A percentage loss reduction reported on one version cannot therefore be transferred to another version without establishing that the topology, load level, generator representation and controls are comparable. This issue is especially important for the 54-bus system, where published studies describe different transformer, reactor and branch representations (Bakare et al., 2021; Jabir et al., 2023).

The broader thesis from which this paper is extracted was designed to minimize fuel cost, active power loss and thermal-generation emissions simultaneously through a constrained AC optimal power-flow framework. During data preparation, however, an important publication-quality issue emerged: the available 54-bus bus and line schedules were sufficiently detailed for a structural audit, but not yet complete enough for a new, fully validated AC loss result. The objective data also described twenty-one named thermal stations, while the network schedule identified only twelve generator-connected buses. Reporting a numerical loss reduction after silently forcing these incompatible datasets together would create a result that looks complete but cannot be defended physically or reproduced independently.

Accordingly, this paper narrows its contribution to a rigorous loss-modelling and data-readiness study. It asks three questions. First, what can be established reliably from the supplied Nigerian 54-bus data? Second, what additional information is required before active loss can be calculated and optimized as an AC network quantity? Third, how should future optimization results be reported so that they can be compared fairly with published Nigerian studies? The answer is developed through an audit of bus and branch records, a formal AC loss formulation and a reproducibility checklist suitable for MATPOWER or an equivalent load-flow environment.

This framing is intentionally conservative. The paper does not convert a generation-demand difference into a verified transmission loss, does not infer branch overloads without thermal ratings and does not claim an optimization improvement that was never produced by a solved AC case. That restraint is not a weakness in the analysis; it is part of the contribution. In power-system optimization, a low objective value has engineering meaning only after the power-flow equations and equipment limits are satisfied (Dommel & Tinney, 1968; Zimmerman et al., 2011).

2. Related Work and Research Gap

Classical power-flow analysis determines the steady-state electrical condition of a specified network. Newton-Raphson remains widely used because its Jacobian formulation is efficient for sparse transmission systems and usually converges rapidly when the model and initial state are well conditioned. Optimal power flow extends this calculation by allowing selected controls to vary while enforcing the nonlinear active- and reactive-power balance equations and operating constraints. In this setting, active loss is not an independent generator parameter; it is a dependent network quantity obtained from the converged voltages and branch flows (Wood et al., 2013; Zimmerman et al., 2011).

Modern OPF research has explored deterministic and population-based solvers. Differential evolution, swarm methods, Sine-Cosine search and other metaheuristics are attractive where the feasible region is non-convex or contains mixed continuous and discrete controls, but their flexibility does not remove the need for feasibility checks (Attia et al., 2018; Biswas et al., 2018; Alencar et al., 2024). Constraint treatment is particularly important in multi-objective applications because an apparently attractive loss value may correspond to violated voltage, reactive-power or branch-flow limits (Avvari & Vinod Kumar, 2022).

In Nigeria, Akwukwuegbu et al. (2017) compared Newton-Raphson power flows on 28- and 52-bus representations, illustrating the sensitivity of reported operating conditions to network size and data definition. Abdulkareem et al. (2021) further demonstrated that even bus representation and numbering can affect convergence behaviour and reported quantities. These studies support a basic methodological principle: a network case must be frozen and validated before optimisation results are interpreted.

For 54-bus studies, Bakare et al. (2021) used MATPOWER with a Firefly-based reactive-power optimisation procedure and reported an active-loss reduction of about 8.07% at full loading alongside voltage-profile improvement. Jabir et al. (2023) analysed a 54-bus, 330-kV system using Newton-Raphson and Artificial Bee Colony optimisation for UPFC placement, reporting improved voltage and reduced losses. The two papers are valuable because they demonstrate that Nigerian 54-bus optimisation is technically feasible, but they address different control problems from generator economic-emission dispatch and do not provide a common machine-readable case against which every number can be reproduced.

Later Nigerian studies use expanded or different models. Ohiero (2023) examined voltage stability on a 56-bus representation, Ozioko et al. (2022) studied wind-penetration effects on active power flow, and Nkan et al. (2023) investigated transfer capability on a 58-bus network. Their findings are useful context but cannot validate the present 54-bus base case directly. The research gap is therefore not simply a shortage of optimisation algorithms. It is the absence of a consistently documented, reproducible 54-bus loss study in which the source data, conversion rules, absolute MW loss, control changes, constraint status and repeated-run procedure are all traceable.

3. Materials and Methods

The study uses the 54-bus bus schedule and associated line schedule embedded in the research work. The bus data contain a source-coded type field, initial voltage magnitude, angle, specified active and reactive generation, active and reactive demand and two additional limit fields whose physical meaning is unresolved. The source coding has been interpreted provisionally as one reference bus, eleven additional generator-controlled buses and forty-two load buses. This mapping is suitable for constructing a draft MATPOWER case but must remain labelled as a modelling assumption until the original data dictionary is recovered.

Direct arithmetic on the supplied bus records gives a total listed active demand of 6,501.9 MW and a total reactive demand of 3,922.0 MVar. The non-slack active generation specified at buses 2-12 totals 4,537.0 MW. These values are data-audit quantities rather than solved operating results. In a valid AC power flow, the slack generator would close the active and reactive balance, and total generation would equal demand plus network losses. The apparent pre-solution shortfall of 1,964.9 MW therefore cannot be interpreted as a loss or deficiency without solving the network.

The line schedule contains 80 records and 62 unique bus-pair corridors, indicating a connected system with several parallel circuits. The available fields include from-bus, to-bus, resistance, reactance, half-line charging and a tap field. All supplied tap values are unity. Verified thermal ratings, branch status flags, phase shifts and adjustable tap limits are absent. A provisional 100-MVA system base was proposed in the methodology chapter for software conversion, but it is not treated here as an original Nigerian data value.

For an N-bus AC system, bus current and voltage are related through $I = Y_{\text{bus}} V$. The active-power injection at bus i is obtained from the real part of the complex power equation. The nodal balance used for validation is $PG_i - PD_i - P_i(V, \delta) = 0$, with an analogous reactive-power equation. After a converged solution, total active generation must satisfy

$$\Sigma PG = \Sigma PD + PL \quad (1)$$

where PG is power generated, PD is the power demand and PL is the total real power loss in MW. A second loss estimate can be formed from solved branch-end flows, and the two methods should agree within the chosen numerical tolerance.

For a simple branch k connecting buses i and j without an off-nominal tap, an equivalent voltage-based loss expression is

$$PL = \Sigma g_k [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)], \quad (2)$$

where g_k is the branch series conductance. Transformer branches require the appropriate tap-adjusted model or direct use of solved branch powers. This distinction matters because using Equation (2) indiscriminately on transformer records can bias the reported loss.

The proposed loss-minimization problem is therefore formulated as a constrained AC OPF. Candidate control variables may include non-slack generator active powers, generator-voltage set points, adjustable tap positions and switchable shunts where verified. The objective is to minimize P_L subject to AC power balance, generator P-Q limits, voltage bounds, transformer and shunt limits and branch-flow constraints. Deterministic MATPOWER OPF should provide a scalar reference, while any stochastic method should use identical network data, limits and a common evaluation budget.

No new numerical optimization is performed in this paper because the final generator capability data, ratings and controls required for an integrated case are incomplete. Instead, the analysis is deliberately split into structural verification, loss-model specification and a readiness assessment. This design prevents provisional assumptions from becoming hidden facts in a published result.

Network quantity	Supplied/derived value	Interpretation
Buses	54	Complete sequential bus schedule
Reference bus	1 (Bus 1, source coding)	Provisional REF mapping
Additional generator buses	11 (Buses 2-12)	Provisional PV mapping
Load buses	42 (Buses 13-54)	Provisional PQ mapping
Listed active demand	6,501.9 MW	Direct sum of demand entries
Listed reactive demand	3,922.0 MVar	Direct sum of reactive demand
Specified non-slack generation	4,537.0 MW	Not a solved total-generation value
Branch records	80	62 unique bus-pair corridors
Network base	100 MVA provisional	Methodology assumption, not verified source data
Nominal voltage	330 kV provisional	Supported by study description; secondary levels unresolved

4. Results

The structural audit confirms a complete 54-row bus schedule with one source-coded reference bus, eleven additional generator buses and forty-two load buses. The corresponding branch file contains 80 records across 62 unique corridors. The topology is connected, which is a necessary precondition for a single-system load-flow solution. The existence of repeated bus pairs is consistent with parallel circuits, although the original circuit identifiers should be recovered before the records are merged or modified.

The bus schedule gives 6,501.9 MW of active demand and 3,922.0 MVar of reactive demand. These totals are internally reproducible and can be used as exact arithmetic checks after conversion to mpc.bus. The non-slack generation total of 4,537.0 MW is likewise reproducible. By contrast, a solved slack output, AC active loss, reactive loss, bus-voltage range and branch-flow distribution are not present in the research work. Those quantities must therefore remain unreported rather than estimated.

The data-readiness audit identifies four critical gaps. First, branch thermal ratings are absent, so an optimization could not determine whether a low-loss schedule overloads a line. Second, all tap values are unity and no verified adjustable tap ranges are provided, so transformer control cannot be included credibly. Third, the final two bus fields conflict with several listed operating points and cannot safely be treated as generator reactive-power limits. Fourth, the cost and emission datasets contain twenty-one stations, whereas the network contains twelve generator-connected buses. This prevents those objective functions from being attached to physical injections without an explicit station-to-bus mapping or documented aggregation.

A separate 2,500-MW dispatch table in the research work provides three generation schedules. Their total generation exceeds the stated demand by 82.7692 MW in the economic case, 110.3708 MW in the emission-oriented case and 190.0644 MW in the equal-weight case. These differences are useful

as balancing residuals, but they are not treated as verified transmission losses because the dispatch source does not provide branch flows or define whether auxiliary consumption, reserve or another quantity is embedded in the balance. The increasing residual nevertheless illustrates why loss should remain an explicit objective when economic and environmental priorities are combined.

Published Nigerian evidence provides context rather than direct validation. Bakare et al. (2021) reported approximately 8.07% active-loss reduction on a Nigerian 54-bus case after reactive-power optimization, while Jabir et al. (2023) also reported loss improvement following UPFC placement. Those results show that network-control decisions can materially change loss, but the percentages should not be compared numerically with the present balancing residuals because the experiments, data and control variables are different.

The immediate result of the present analysis is therefore a verified statement of what the dataset can and cannot support. Structural connectivity, bus counts, demand totals, specified generation entries and branch impedances can be audited. A new active-loss minimum, voltage improvement or congestion-relief percentage cannot yet be established. For journal reporting, that boundary is essential: a reproducible null result is preferable to a precise-looking value that is not generated by a defensible AC model.

Data item	Status	Consequence for loss analysis
Branch R/X/B	Available	Ybus and solved branch flows can be formed
Branch ratings	Missing	Overload feasibility cannot be verified
Adjustable tap limits	Missing	Transformer optimisation cannot be claimed
Generator Q limits	Unresolved	Reactive feasibility requires source confirmation
Shunt/reactor schedule	Not supplied	Reactive controls cannot be reproduced
Station-to-generator-bus mapping	Missing	Cost/emission objectives cannot be integrated physically
Solved runpf/runopf outputs	Not supplied	No new AC loss minimum can be reported

Dispatch emphasis	Total generation (MW)	Generation – 2,500 MW (MW)	Interpretation
Economic	2582.7692	82.7692	Balancing residual; not a verified AC loss
Emission	2610.3708	110.3708	Balancing residual; not a verified AC loss
Equal cost-emission	2690.0644	190.0644	Balancing residual; not a verified AC loss

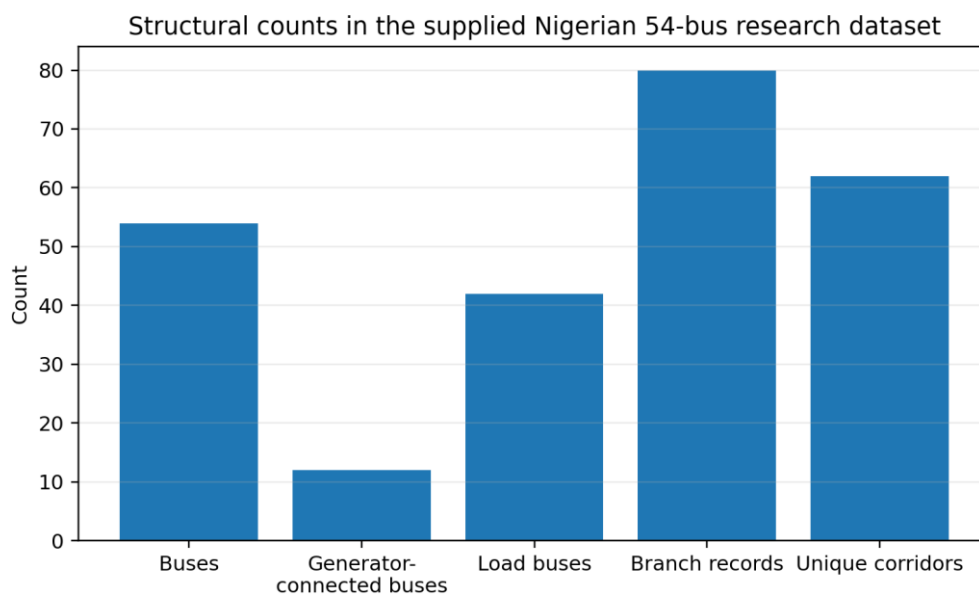


Figure 1. Structural counts in the supplied Nigerian 54-bus research representation.

5. Discussion

The most important implication is that power-loss optimization in a national-grid model is as much a data-governance problem as an algorithm-selection problem. Metaheuristics can search a complicated decision space, but they cannot correct a branch rating that was never supplied or determine which of twenty-one thermal stations belongs to which of twelve generator buses. If incompatible data are forced into one case, the optimization may converge numerically while solving a system that never existed in the source data.

This observation helps explain why percentage-only loss comparisons are often difficult to interpret. A reduction of 8% can be important or modest depending on the original MW loss, loading condition and controls. The absolute base loss, final loss, total demand, voltage limits and control settings should therefore be reported alongside the percentage change. The same principle applies when comparing network versions. A 54-bus result should not be validated with a 52- or 58-bus value merely because all models represent Nigeria.

A second implication concerns objective interaction. The separate dispatch data show that an equal cost-emission weighting produced the largest generation-demand residual among the three reported schedules. Although that residual is not a verified AC loss, the pattern is consistent with the physical argument that a compromise between generator-level objectives may still be poor from the network perspective. Generator location matters. A schedule that is attractive when transmission is ignored can shift power over longer or more resistive paths and thereby increase the generation required to serve the same demand.

A third implication is methodological fairness. If a future IWDO, WDO, PSO or DE experiment is performed on this system, equal iteration counts alone are insufficient because algorithms may use different numbers of power-flow evaluations per iteration. The defensible comparison is a common objective-evaluation budget, a shared AC evaluator, identical repair and feasibility rules, common random seeds where applicable and reporting of all failed or infeasible runs. Multi-objective methods should additionally report Pareto quality and diversity rather than one selected compromise (Deb et al., 2002; Yuan et al., 2017).

For Nigerian transmission research, the required next step is clear. One authoritative 54-bus version should be frozen; its bus, branch, transformer, shunt and generator tables should be version controlled; and every transformation into MATPOWER should be documented. If multiple physical stations inject at one modelled generator bus, the aggregation rule should preserve capacity and define how cost and emission curves are combined. Only after that mapping is established should cost, emissions and loss be optimised simultaneously.

The paper therefore reframes active-loss minimisation as a reproducibility problem with an optimisation stage, rather than an optimisation problem with data added afterward. This ordering is consistent with the original OPF principle of solving a physically feasible network state and with contemporary concerns about reproducible computational research.

6. Minimum Reporting Standard for a Nigerian 54-Bus Loss Study

A publishable loss study on this case should provide, at minimum, the exact network source and data year; base MVA; bus, generator and branch matrices; transformer and shunt controls; branch MVA ratings; voltage and reactive-power limits; the initial operating condition; the solved base-case loss in MW; and the optimisation control vector. If any field is assumed, the assumption should be identified separately from source data.

The load-flow report should include convergence status, iteration count, total active and reactive generation, total demand, active and reactive loss, minimum and maximum bus voltages and all limit violations. The loss should be cross-checked as total generation minus demand and as the sum of branch losses. Disagreement between the two calculations should trigger a model audit rather than be hidden through rounding.

For stochastic optimization, at least the population size, maximum evaluations, parameter values, random seeds, constraint-handling method, failed-run policy, number of independent runs and descriptive statistics should be disclosed. Best-run values alone are not enough to establish robustness. Where a new algorithm is claimed, an ablation study should separate the effect of the proposed components from ordinary parameter tuning.

Finally, comparisons with prior Nigerian studies should be labelled as direct, approximate or contextual. Direct comparison requires a demonstrably equivalent network and objective. If the network differs, the prior result can motivate the study but should not be used as a numerical benchmark.

Reporting element	Minimum requirement
Network identity	Exact source, data year, bus numbering and version
Electrical base	baseMVA, voltage bases and conversion method
Base-case result	Convergence, ΣPG , ΣPD , MW/MVAr loss and voltage range
Constraints	P/Q limits, voltage limits, branch ratings, taps and shunts
Loss reporting	Absolute MW loss and percentage change
Optimization	Control vector, bounds, stopping rule and evaluator

Reporting element	Minimum requirement
Stochastic comparison	Common budget, seeds, all-run statistics and failed-run policy
Reproducibility	Case file, code, parameters, raw outputs and README

8. Conclusion

This paper extracted the active power-loss strand of a broader Nigerian 54-bus multi-objective OPF study and converted it into a focused, publication-ready methodological analysis. The supplied data define a connected 54-bus research representation with twelve generator-connected buses, forty-two load buses, 6,501.9 MW of listed demand and 80 branch records across 62 unique corridors. They do not yet provide all the information needed to claim a new solved transmission loss or a loss-reduction percentage.

The central conclusion is that credible loss minimization requires a frozen and traceable network case before algorithmic optimization begins. Branch ratings, generator capability limits, control-device data and the mapping of objective coefficients to network generators are not optional details. They determine the feasible region and the physical meaning of the reported loss. Future work should complete that data reconciliation, validate the Newton-Raphson base case, report absolute MW loss and then compare deterministic and stochastic optimizers under equal evaluation conditions. Until those steps are completed, the responsible scientific conclusion is not an invented improvement but a clearly defined path to a reproducible one.

References

- Abdulkareem, A., Alayande, A. S., Somefun, T. E., & Ette, E. V. (2021). Investigating the effects of bus numbering in a radial transmission network using load-flow study. *Heliyon*, 7(5), e07098. <https://doi.org/10.1016/j.heliyon.2021.e07098>
- Adegoke, S. A., Sun, Y., Adegoke, A. S., & Ojeniyi, D. (2024). Optimal placement of distributed generation to minimize power loss and improve voltage stability. *Heliyon*, 10(21), e39298. <https://doi.org/10.1016/j.heliyon.2024.e39298>
- Adetokun, B. B., & Muriithi, C. M. (2021). Impact of integrating large-scale DFIG-based wind energy conversion system on the voltage stability of weak national grids: A case study of the Nigerian power grid. *Energy Reports*, 7, 654–666. <https://doi.org/10.1016/j.egyr.2021.01.025>
- Akwukwuegbu, I. O., Nosiri, O. C., Agubor, C. K., & Olubiwe, M. (2017). Comparative power flow analysis of 28 and 52 buses for 330 kV power grid networks in Nigeria using Newton–Raphson method. *International Journal of Recent Engineering Research and Development*, 2(5), 1–23.
- Alencar, M. V., da Silva, D. N., Nepomuceno, L., Martins, A. C. P., Balbo, A. R., & Soler, E. M. (2024). Discrete optimal power flow with prohibited zones, multiple-fuel options, and practical operational rules for control devices. *Applied Energy*, 358, 122545. <https://doi.org/10.1016/j.apenergy.2023.122545>
- Avvari, R. K., & Vinod Kumar, D. M. (2022). Multi-objective optimal power flow with efficient constraint handling using hybrid decomposition and local dominance method. *Journal of The Institution of Engineers (India): Series B*, 103, 1643–1658. <https://doi.org/10.1007/s40031-022-00748-0>
- Bakare, G. A., Ibrahim, K. A., Haruna, Y. S., & Abba Gana, M. (2021). Reactive power optimization of Nigerian grid system using Firefly Algorithm for power loss reduction and voltage profile enhancement. *Journal of Multidisciplinary Engineering Science and Technology*, 8(3), 13675–13682.
- Biswas, P. P., Suganthan, P. N., Mallipeddi, R., & Amarutunga, G. A. J. (2018). Optimal power flow solutions using differential evolution algorithm integrated with effective constraint handling techniques. *Engineering Applications of Artificial Intelligence*, 68, 81–100. <https://doi.org/10.1016/j.engappai.2017.10.019>
- Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6(2), 182–197. <https://doi.org/10.1109/4235.996017>
- Dommel, H. W., & Tinney, W. F. (1968). Optimal power flow solutions. *IEEE Transactions on Power Apparatus and Systems*, PAS-87(10), 1866–1876. <https://doi.org/10.1109/TPAS.1968.292150>
- Eze, C. U., Ogbuefi, U. C., & Anyaka, B. O. (2023). Optimising the size and placement of embedded energy generators for distribution system loss reduction and voltage improvement. *International Journal of Power and Energy Conversion*, 14(2–3), 176–193. <https://doi.org/10.1504/IJPEC.2023.134874>
- Ghasemi, M., Ghavidel, S., Ghanbarian, M. M., Gharibzadeh, M., & Azizi Vahed, A. (2014). Multi-objective optimal power flow considering the cost, emission, voltage deviation and power losses using multi-objective modified imperialist competitive algorithm. *Energy*, 78, 276–289. <https://doi.org/10.1016/j.energy.2014.10.007>
- Huy, T. H. B., Kim, D., & Vo, D. N. (2022). Multiobjective optimal power flow using multiobjective search group algorithm. *IEEE Access*, 10, 77837–77856. <https://doi.org/10.1109/ACCESS.2022.3193371>
- Jabir, G., Bakare, G. A., & Haruna, Y. S. (2023). Optimal deployment of unified power flow controller on Nigerian 330 kV grid using Artificial Bee Colony. *International Journal of Research and Innovation in Applied Science*, 8(8), 18–31. <https://doi.org/10.51584/IJRIAS.2023.8803>

- Khunkitti, S., Siritaratiwat, A., & Premrudeepreechacharn, S. (2021). Multi-objective optimal power flow problems based on slime mould algorithm. *Sustainability*, 13(13), 7448. <https://doi.org/10.3390/su13137448>
- Nkan, I., Obi, P., Natala, H., & Okoro, O. (2023). Investigation of the transfer capability of the Nigerian 330 kV, 58-bus power system network using FACTS devices. *ELEKTRIKA—Journal of Electrical Engineering*, 22(1), 53–62. <https://doi.org/10.11113/elektrika.v22n1.422>
- Ohiero, P. O. (2023). Application of Newton Raphson method to voltage stability analysis of the Nigeria 330 kV transmission grid. *International Journal of Engineering Research & Technology*, 12(1), 186–195.
- Ozioko, C. O., Ugwuanyi, N. S., Ekwue, A. O., & Odeh, C. I. (2022). Wind energy penetration impact on active power flow in developing grids. *Scientific African*, 18, e01422. <https://doi.org/10.1016/j.sciaf.2022.e01422>
- Wood, A. J., Wollenberg, B. F., & Sheblé, G. B. (2013). *Power generation, operation, and control* (3rd ed.). Wiley.
- Yuan, X., Zhang, B., Wang, P., Liang, J., Yuan, Y., Huang, Y., & Lei, X. (2017). Multi-objective optimal power flow based on improved strength Pareto evolutionary algorithm. *Energy*, 122, 70–82. <https://doi.org/10.1016/j.energy.2017.01.071>
- Zimmerman, R. D., Murillo-Sánchez, C. E., & Thomas, R. J. (2011). MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education. *IEEE Transactions on Power Systems*, 26(1), 12–19. <https://doi.org/10.1109/TPWRS.2010.2051168>