

Multi-objective Bacterial Foraging Optimisation of On-Load Tap-Changer Operations for Voltage Regulation and Loss Reduction: Evidence from the IEEE 30-Bus System and a Nigerian 63-Bus Feeder

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Abstract: This study evaluates a bacterial foraging algorithm (BFA) for coordinating on-load tap-changer (OLTC) settings with two operational objectives: reducing bus-voltage deviation and limiting tap operations. The method was assessed using a standard IEEE 30-bus test system and the 63-bus Government Reserved Area (GRA) feeder in Bauchi, Nigeria. Network power-flow calculations were conducted in MATLAB R2019b with the PSAT toolbox, and the BFA search was configured with four bacteria, ten chemotactic steps, four swim steps, four reproduction steps, two elimination–dispersal events and a 0.1 run-length parameter. The reported IEEE 30-bus results show active losses declining from 17.528 to 15.710 kW (10.37%), reactive losses from 68.888 to 61.340 kVAr (10.96%), voltage deviation from 0.9477 to 0.7115 p.u. (24.92%), and daily tap operations from 17 to 11 (35.29%). For the Bauchi GRA feeder, active losses declined from 171.65 to 113.56 kW (33.82%), reactive losses from 129.59 to 98.76 kVAr (23.79%), voltage deviation from 0.6900 to 0.6420 p.u. (6.96%), and tap operations from 22 to 14 (36.36%). The findings indicate that BFA-based OLTC scheduling can improve the reported loss and switching indicators across a benchmark network and a field-derived Nigerian feeder. Interpretation is constrained by inconsistencies in the source thesis concerning voltage limits, the definition of voltage deviation, and some reported percentage improvements. The results should therefore be treated as simulation evidence requiring reproducibility checks, sensitivity analysis and validation against time-varying feeder measurements before operational deployment.

Keywords: On-load tap changer, bacterial foraging algorithm, distribution network, voltage regulation, active power loss, reactive power loss, tap-operation minimization, Nigerian distribution feeder

INTRODUCTION

Electrical distribution network (EDN) represents the last stretch of the power system that brings electricity from the substation to the end-users. As a result of their performance, they play a pivotal role in ensuring the supply quality and operational efficiency. The distribution utilities are required to keep the bus voltage within the acceptable limits, minimize technical power losses and ensure the reliability of power supply despite changing demand and network conditions (Krishna, 2024; Narges et al., 2023). These goals are interdependent and a change in a voltage at one location may impact losses or operating conditions at another location of the feeder. The voltage regulation, therefore, has to be taken into account along with the efficiency of the network and the limitations of its distribution equipment.

The radial configuration is common in distribution systems due to its relatively simple structure and the ease with which protection coordination can be achieved, such as for overcurrent protection (Hamed et al., 2024). But, loading variations and voltage drops can cause bus voltages to deviate from the desired value. Some of the actions taken in response to these conditions are the installation of network switching, load balancing and voltage-control equipment. In this context, the aim of effective voltage regulation is to optimize voltage profile while minimizing losses and any unwanted control actions (Hamza et al., 2022). Keeping the voltage within certain operating ranges is critical, as the utility assets and customer equipment are built to operate under certain voltage (Ibrahim, 2023).

Tap changers are used to regulate the voltage directly by varying the turns ratio of a transformer. Generally, they are classified as de-energised or off-circuit tap changers, which are adjusted when the transformer is not carrying load, and on-load tap changers (OLTCs), which allow tap changes to be made while the transformer is energised (Roshni et al., 2024). Under specific circumstances, when load and feeder characteristics change over time, OLTCs can be very beneficial. How effective they are, however, depends on the control settings that dictate when and how the tap position is changed. Mechanical switching may lead to contact wear, stress caused by arcing, maintenance needs; frequent switching may cause additional maintenance needs. Therefore, voltage-control strategies are required to correct the voltage deviations, but also to prevent excessive number of taps.

Conventional OLTC control commonly relies on measured voltage, predefined dead bands and time delays. Such arrangements are established and relatively straightforward to implement, but fixed settings may not provide the best compromise across different loading patterns and feeder conditions. Optimisation methods can help identify tap settings that balance competing objectives, including voltage deviation, power losses and the number of tap changes. This is a multi-objective operational problem because improving one measure does not necessarily improve all the others. A suitable optimisation approach must therefore explore candidate solutions effectively while accommodating discrete tap positions and an objective function that may not be differentiable.

This study applies the bacterial foraging algorithm (BFA) to the optimisation of OLTC settings in radial distribution networks. Introduced by Passino (2002), BFA is a metaheuristic optimisation method

inspired by the foraging behaviour of *Escherichia coli* bacteria. Its principal mechanisms are chemotaxis, swarming, reproduction and elimination–dispersal, which together support the exploration and refinement of candidate solutions (Xing and Gao, 2014; Natasha et al., 2021). The algorithm is considered here because it can search complex solution spaces without requiring gradient information. Its suitability for this application must nevertheless be established through the resulting network performance and transparent reporting of the optimisation procedure, rather than assumed from the algorithm’s biological inspiration alone.

The proposed approach is evaluated on two systems: the IEEE 30-bus benchmark and a 63-bus feeder serving the GRA area of Bauchi, Nigeria. The feeder data are reported as having been obtained from records supplied by Jos Electricity Distribution (JED PLC). The evaluation examines the trade-off between voltage deviation, active and reactive power losses, and OLTC operation frequency. The study’s principal aim is to determine whether BFA-based OLTC tuning can improve voltage conditions and reduce network losses while limiting unnecessary tap changes in both a benchmark system and a locally relevant feeder. By considering these performance measures together, the work seeks to assess the practical value of optimisation-based voltage control under different distribution-network conditions.

Research context and contribution

Research on OLTC control spans conventional automatic voltage regulation, electronically assisted switching, optimisation-based control and learning-based approaches. The source thesis reviews proportional–integral control, solid-state OLTCs, artificial bee colony methods, reinforcement learning and other coordinated voltage-control strategies. These approaches demonstrate that voltage regulation is a multi-variable control problem: a controller must respond to changing operating conditions while respecting the discrete and finite tap positions of the transformer.

BFA is relevant where the objective function combines non-smooth and discrete decisions. Its chemotaxis stage explores local directions, swarming models’ population interaction, reproduction retains better-performing candidates, and elimination–dispersal introduces diversification (Passino, 2002). The algorithm does not, by itself, guarantee a global optimum for a finite run; performance depends on parameter choices, encoding, objective scaling and repeated-run behaviour. For this reason, an evaluation should report the full objective function, bounds, stopping conditions, random seeds, repeated-run statistics and comparisons against clearly specified baselines.

The contribution claimed here is an application-level evaluation of a multi-objective BFA-OLTC method on both a standard test system and a Nigerian feeder, with results reported for losses, voltage deviation and daily tap operations. The practical value lies in testing the approach beyond a benchmark system. The evidence is preliminary rather than a definitive proof of superiority because the source material does not provide enough information to reconstruct every optimisation run or independently verify all reported metrics.

MATERIALS AND METHODS

Study systems and simulation environment. The benchmark system was the IEEE 30-bus network. The second system was the Bauchi GRA feeder, described as an 11-kV radial network comprising 63 buses and 62 branches, with total real load of 3,977.4 kW and reactive load of 1,703.4 kVAr. The source reports MATLAB R2019b and the PSAT toolbox as the simulation environment. The study's distribution-network data were attributed to JED PLC records. The transformer description in the thesis includes a 33/11-kV, 750-kVA, three-phase, 50-Hz autotransformer with an OLTC; the exact relationship between this equipment description and the feeder model should be clarified in a submission-ready methods appendix.

Optimisation objective. The thesis defines a multi-objective formulation that assigns equal weights to total bus-voltage deviation and OLTC switching activity. In general form, the objective can be expressed as $J = wV \cdot TVD + wT \cdot NT$, where TVD represents the study's total voltage-deviation measure, NT is the number of tap operations over the evaluation period, and wV and wT are weighting factors. The thesis states that $wV = wT = 1$. Because TVD and tap count have different units and scales, an improved journal version should explicitly state whether the terms were normalised before addition; this detail is not sufficiently clear in the supplied document.

Constraints. The optimisation is described as subject to power-flow equality constraints and inequality constraints on bus voltages, line currents and equipment capacity. The thesis reports voltage limits of 0.85–1.15 p.u. for the IEEE 30-bus system and 0.95–1.05 p.u. for the GRA feeder. However, the results discussion also refers to other voltage bands and describes some buses as violating a limit that is not consistently applied. These limits and the definition of a voltage violation must be reconciled against the actual model before publication. Tap positions are discrete and bounded by the OLTC's stated operating range.

BFA configuration. The reported parameter values were: search-space dimension 2; bacterial population 4; chemotactic steps 10; swim steps 4; reproduction steps 4; elimination–dispersal steps 2; run length 0.1; reproduction population $S_r = S/2$; elimination–dispersal probability 0.25; attractant depth 0.1; attractant width 0.2; repellant height 0.1; and repellant width 10. These values are reproduced from the thesis rather than independently tuned in this article. A reproducible implementation should additionally disclose the variable encoding, random-number seed, number of independent runs, termination rule, exact power-flow solver settings and any repair procedure for infeasible tap combinations.

Evaluation measures. The reported outputs include active power loss, reactive power loss, maximum and minimum bus voltage, voltage-deviation measure, number of voltage violations and tap operations over 24 hours. Percentage reduction was recalculated from the before-and-after values as $100 \times (\text{baseline} - \text{optimised})/\text{baseline}$. This recalculation is used where it differs slightly from rounded percentages in the source.

RESULTS

Table 1 summarises the reported baseline and optimised outcomes for both systems. On the IEEE 30-bus network, active power loss fell by 1.818 kW, equivalent to 10.37%, and reactive power loss fell by 7.548 kVAr, equivalent to approximately 10.96%. Voltage deviation decreased from 0.9477 to 0.7115 p.u., a reduction of approximately 24.92%. Tap operations over 24 hours decreased from 17 to 11, a reduction of 35.29%. The reported number of voltage violations decreased from three to one. For the Bauchi GRA feeder, active power loss fell by 58.09 kW, equivalent to approximately 33.82%, while reactive power loss fell by 30.83 kVAr, or approximately 23.79%. Tap operations declined from 22 to 14 per 24 hours, a 36.36% reduction. The voltage-deviation value decreased from 0.6900 to 0.6420 p.u. (approximately 6.96%). The thesis reports zero voltage violations in both baseline and optimised cases. Thus, the clearest improvement in the GRA case is the reduction in losses and switching frequency; the voltage-deviation improvement is more modest than the thesis's stated 24.5% figure.

These results suggest that the BFA-selected tap settings can improve the combined performance indicators in the tested simulations. However, the results do not establish statistical robustness because repeated independent runs and variation measures were not provided. Moreover, the reported IEEE minimum-voltage values and stated voltage-violation counts appear inconsistent with the voltage limits described in the methods. Those discrepancies should be corrected using the original simulation output rather than resolved by assumption.

Table 1. Reported performance before and after BFA-OLTC optimisation.

Metric	IEEE 30-bus base case	IEEE 30-bus BFA-OLTC	Bauchi GRA 63-bus base case	Bauchi GRA 63-bus BFA-OLTC
Active power loss (kW)	17.528	15.710	171.65	113.56
Reactive power loss (kVAr)	68.888	61.340	129.59	98.76
Voltage deviation (p.u.)	0.9477	0.7115	0.6900	0.6420
Tap operations per 24 h	17	11	22	14
Voltage violations (count)	3	1	0	0
Minimum bus voltage (p.u.)	0.9985 (Bus 30)*	0.9744 (Bus 8)	0.9599 (Bus 41)	0.9695 (Bus 41)
Maximum bus voltage (p.u.)	1.080 (Bus 11)	1.070 (Bus 12)	1.000 (Bus 1)	1.010 (Bus 41)

The minimum-voltage entry for the IEEE base case is reproduced from the source thesis; it appears inconsistent with other reported values and should be verified against the original simulation output.

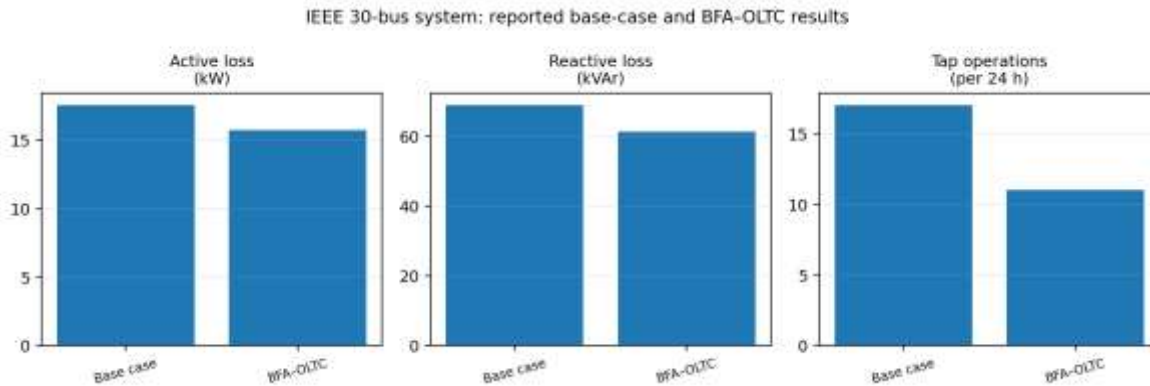


Figure 1. Base-case versus BFA-OLTC outcomes for the IEEE 30-bus system.

DISCUSSION

The two-system comparison is useful because it tests the approach on a standard benchmark and a feeder grounded in Nigerian distribution data. The IEEE results indicate moderate reductions in active and reactive losses accompanied by a substantial decrease in the number of tap operations. On the GRA feeder, the absolute and relative active-loss reduction is larger, while switching frequency also declines. These patterns are consistent with the idea that an optimised tap schedule can improve the operating point of a radial network, although tap control alone cannot remove losses arising from conductor resistance, topology or load distribution.

Reducing tap operations matters because mechanical OLTCs have finite contact and mechanism life, and switching can contribute to maintenance requirements. The reported reduction of around one-third in daily operations is therefore operationally relevant. Nevertheless, the study does not quantify contact wear, maintenance costs, transformer temperature, switching transients or lifetime extension. Such benefits should be described as potential implications, not measured outcomes.

An important methodological issue is the objective-function scaling. Adding an unnormalised voltage-deviation sum to a raw tap-operation count can cause the numerical magnitude of one term to dominate the search. Future work should report the exact formula, normalisation method and weighting rationale, then perform a sensitivity analysis across alternative weights. In addition, BFA is stochastic. Results from a single run cannot establish that the selected settings are consistently better than alternatives. At minimum, multiple runs should be compared using best, mean, standard deviation and worst-case outcomes, alongside suitable baseline controllers and algorithms.

Finally, simulation evidence should not be treated as field validation. The feeder model's load profile, line parameters, tap constraints and the source of the 24-hour operating sequence should be documented. A practical deployment would require time-series load-flow analysis, hardware and protection compatibility checks, and controlled testing with the distribution utility.

CONCLUSION

This study examined BFA-based optimisation of OLTC switching operations for voltage regulation and loss reduction in the IEEE 30-bus system and the Bauchi GRA 63-bus feeder. According to the reported simulations, the IEEE case achieved reductions of 10.37% in active losses, approximately 10.96% in reactive losses and 35.29% in daily tap operations, while voltage deviation decreased by approximately 24.92%. The GRA feeder achieved reductions of approximately 33.82% in active losses, 23.79% in reactive losses and 36.36% in tap operations; the voltage-deviation value decreased by approximately 6.96%.

The results support further investigation of BFA as a decision-support method for OLTC scheduling in radial distribution networks. The next research stage should resolve the reported data inconsistencies, use normalised multi-objective functions, compare BFA with conventional and alternative optimisation methods over repeated runs, and validate the approach using time-series feeder data. Only after these checks should claims about general superiority or practical deployment be made.

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