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A cost-effective multi-objective optimization technique for automatic voltage regulator placement in radial distribution power network.

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Abstract

Optimizing distribution network operations has emerged as critical priority with a key focus on leveraging distribution system network enhancement to drive improvement in network performance. This study aims to determine the optimal placement of Automatic Voltage Regulators (AVRs) in radial distribution networks to achieve superior performance. A comparative analysis of conventional and non-conventional approaches revealed the efficacy of the Adaptive and Dynamic Inertia Weight acceleration Coefficient (ADIWACO) Particle Swarm Optimization (PSO) algorithm in optimizing AVR placement. Notably, the loss sensitivity factor and ADIWACO PSO variant achieved significant percentage error reductions of 50% and 51%, respectively. Furthermore, the ADIWACO variant demonstrated superior optimal searching capabilities, with a standard deviation error of 0.000426. Economic analysis validated the results, confirming that the real power loss reduction achieved through optimal AVR placement yields substantial economic benefits.

Keywords: Loss sensitivity analysis, Particle swarm optimization, automatic voltage regulator, benefit-to-cost ratio, ADIWACO

1. Introduction

The Voltage profile enhancement and loss minimization in radial distribution networks through automatic voltage regulator placement has been a thorn in the flesh of researchers in recent years. So many approaches, such as those reported in (Bhadoriya, et al., 2022); (Samson, et al., 2024) and (Ibrahim, et al., 2018) have received limited attention because of the financial constraints of their implementation in third-world countries. However, the approaches by (Okwuosa, et al., 2024) are making waves in the academic communities in Africa. Voltage stability and loss minimization issues could be handled economically by implementing load management control measures. Unlike third-world countries, the United States and some other developed countries prioritize load management by implementing load control measures. Significant average load reductions were achieved, ranging from 1 kW per point for winter heating to 28.7 kW per point for irrigation pumps (Onah et al. 2022). Canadian utilities, such as those in Ontario and Quebec, adopted similar programs. This makes the utilities to see voltage profile enhancement and loss reduction as serious concerns. They incentivize load management by offering various rewards that include bill credits: \$1-5 per month for water heaters, \$1.25-12 per month for air conditioners, and \$15-29 per year for irrigation. The UK's Economy 7 program provides discounted nighttime electricity rates. Similar incentives and pricing options are available in most developed countries (Khedkar, 2017).

In contrast, Nigeria and many sub-Saharan African countries have made limited efforts to educate customers about the benefits of demand-side management (DSM). Unlike developed countries, there are no penalties for frequent blackouts or rewards for adopting DSM programs. The lack of regulation and stakeholder engagement, particularly from the National Electricity Regulatory Commission (NERC), poses a significant challenge to Africa's electricity sector (Khedkar, 2017). The Nigerian National Grid's declining performance can be attributed to various factors, including ohmic losses, persistent voltage declines, and insufficient reactive reserve (Onah et al., 2019). To address these challenges, researchers have explored several approaches, as discussed in (Onah et al., 2021; 2023; 2024; 2025). In non-conventional methods, the Flexible Alternating Current Transmission Systems (FACTS) have been exploited in developed national grids; conventional/traditional approaches, like automatic voltage regulators, remain a priority for underdeveloped grids. This paper presents a comprehensive solution to optimize the placement of automatic voltage regulators (AVRs) in the Nigerian National Grid. The proposed method formulates a multi-objective problem to minimize total power losses and system voltage deviation. Key constraints, such as maximal deviation of tap position and standardized nominal values of AVRs, are considered. To avoid numerical convergence issues, the tap position of each AVR is treated as a state variable in the Newton-Raphson load flow algorithm. PSO has been applied to a wide range of applications Researchers, including Ghanegaonkar and Pande (2015) and Laxmidevi (2017), have utilized PSO for optimal placement of voltage regulators in radial distribution systems to improve voltage profiles and minimize power losses.

To overcome convergence difficulties inherent in the traditional methods of solving optimal power flow problems, Okwuosa et al., 2024) made an exploit of particle swarm optimization problem to achieve a desired result. However, the work neither addressed the choice of the variant for the simulation nor emphasize the economic benefit of using the nature inspired approach. This study develops a model for optimal placement of auto-transformers in radial distribution systems using PSO. The algorithm optimizes tap settings of voltage regulators to improve voltage profiles and minimize power losses. Tap settings and locations are treated as discrete variables. The primary objective is to minimize the number of voltage regulators, reducing overall costs. A case study of the main power distribution network in Nigeria will be conducted. Simulation studies using PSAT/MATLAB SIMULINK will evaluate the impact of AVR placement using the proposed PSO algorithm. Results will be benchmarked against the Loss Sensitivity Factor (LSF) algorithm. Joseph et al., (2022) attempted to address the challenges of reconfiguring distribution system topology by evaluating the state of the switch devices and the power flow through the distribution lines. The work introduced redundant lines to increase ease of convergence. However, the exact positioning of the AVR is a major concern. Jesus., (2023) attempted to change the network configuration topology and enhance voltage profiles of the feeder, minimize ohmic losses by using mixed integer linear programming model to properly place the AVR. Although, the work was tested in IEEE 33 bus and validated in IEEE 69 and IEEE 119 buses, the approach is usually difficult to solve large scale problems.

Previous studies, such as those by Sekyere et al. (2024), Ekinci et al. (2023), Sivanandhan et al. (2022), and Sain et al. (2023), did not investigate various PSO variants and economic benefits of loss reduction. This study addresses these gaps through a comparative approach to PSO variant selection and economic evaluation of real power losses. The study made a choice of ADIWACO PSO approach for optimal classical proportional integral derivative tunning owing to its ease of facilitating enhancement of convergence speed, stability and ruggedness, thereby addressing the inherent challenges observed in the rest of the five PSO variants. The rest of the variants are prone to convergence difficulties. The excellent dynamic response and computational efficiency of the ADIWACO algorithm makes it a standout PSO variant for the simulation.

2.1 Material and Methods

2.1.1 Problem Formulation

The AVR comprises the PID controller the amplifier, the exciter, the generator, the sensor and the summer comparator. The transfer function is the ratio of the output voltage signal and the input voltage signal. The difference between the input voltage and the output signal from the sensor which is known to have high frequency noise gives out the error signal as seen in Figure 1. The error signal forms the objective function which is required to be minimized by ADIWACO PSO variants. The gains of the PID controller take the error signal which is optimally tuned using ADIWACO PSO variants.

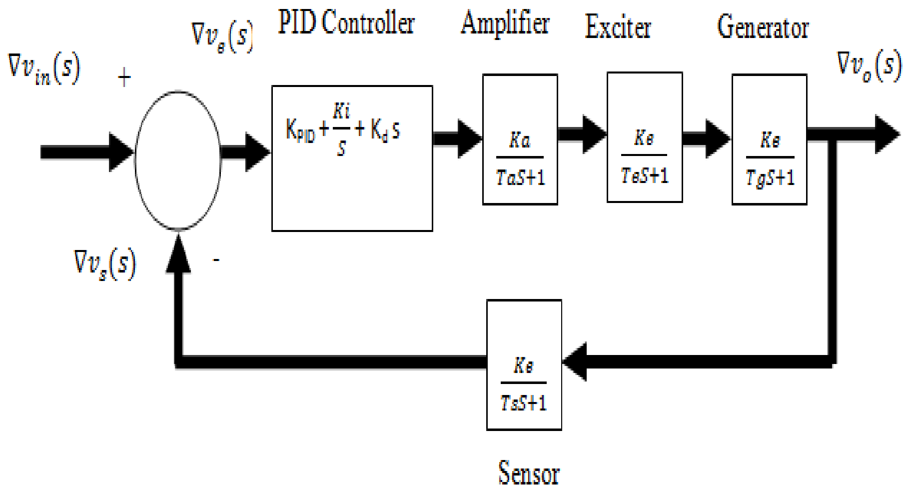

Figure 1: The Block Diagram of the AVR

2.1.2 PROPOSED ADIWACO PSO

The concepts of Standard Particle Swarm Optimization (PSO) variant obtained by (Kennedy and Eberhart, 1995 were modified by (Sekyere et al., 2023) through the fine tuning of the weight and the inertia coefficients. In a multidimensional search space, particles' positions and velocities are represented as vectors. In this context, buses in the power system are represented by particles. The velocity of each particle is iteratively updated using the PSO algorithm's velocity update equation.

2.2. The Loss Sensitivity Analysis

The real power loss at each transmission line is given by Onah et al (2021):

$$P_{loss} = \left[\frac{(p_i^2 + Q_i^2)}{V_i^2}\right] R_i \qquad (1)$$

The total power loss, P_{loss}, of the distribution line is the summation of all the losses at the section

An exploit of sensitivity analysis is made to select the candidate feeder for the location of the AVR. This is used to identify the bus that has the most significant impact on the performance of the network. It takes care of the loss and the voltage profile of the network.

The Loss sensitivity factor (LSF) is given by Devi et al (2021) and expressed as:

$$LSF = \frac{\Delta P_{loss}}{Q_{@location}} \qquad (2)$$

where $Q_{@location}$ is the reactive power at a particular location and ΔP_{loss} is the difference in real power losses between the new and old load flow studies due to the load increase.

The bus with the highest LSF value is considered the best candidate for AVR placement, as it has the most significant impact on the network's performance, including both power loss and voltage profile.

$$V_i^{t+1} = \omega V_i^t + C_1 U_1^t \,(Pb_i^t - P_i^t) + C_2 U_2^t \,(gb_i^t - P_i^t) \qquad (3)$$

Each individual particle moves from the current position to the next one by using the modified velocity. Where

V_i^{t+1} = the velocity of the particle after the update ω = weight, V_i^t is the velocity of a particle

C_1 and C_2 is the acceleration coefficients

Pb_i^t= Personal best location of a particle at a given iteration

gb_i^t= optimal position of individual particle at a given iteration t.

$$V_i^{t+1} = \omega V_i^t \tag{4}$$

When $C_1 > 0$ and $C_2 = 0$, all particles have affinity with a single point in the entire swarm. Thus, the update velocity will become

$$V_i^{t+1} = \omega V_i^t + C_2 U_2^t \,(gb_i^t - P_i^t) \tag{5}$$

At a condition when $C_1 = C_2$, close attraction between pbest and gbest exists.

$$x_1(t+1) = X_1(t+) + V_i(t+1) + C_2\,(f(t) - x_1(t)) \tag{6}$$

The ADIWACO PSO introduces exploitation and exploration in the hyperparameters of the standard PSO variant by updating the ω and the coefficients.as seen in (7)

$$\omega = \mu \tan ð \tag{7}$$

Where $\mu = \frac{personal\ best\ minus\ global\ best}{global\ best}$ (8)

Again, $ð = \omega_{max} - \frac{(\omega_{max} - \omega_{min}) \text{ x current iteration}}{maximum\ nuber\ of\ current\ iteration}$ (9)

On the other hand, $C_1 = C_2 = \mu cosh Ø$, (10)

where $Ø = C_{max} - \frac{(C_{max} - C_{min}) \text{ x current iteration}}{maximum\ nuber\ of\ current\ iteration}$ (11)

The hyperbolic trigonometric function seen in equation (10) plays important roles in ADIWACO PSO algorithm by improving its exploration and exploitation capabilities. The ω makes use of the bounded nature of the trigonometric functions to pave way for smooth transition at the beginning of the optimization.

Table 1: ADIWACO PSO for the Parameter tuning

Parameters	Values
Population Size (N)	12
Dimension	4
Simulation time	5
Maximum inertia time	1
Minium Inertia weight	0.1
Maximum acceleration coefficients	6
Minimum acceleration coefficients	2
Maximum Number of Iterations	1000
Controller gain boundaries	[2 0]

3.1 Algorithm for optimal location of AVR

Step 1: Start

Step 2: Define the ADIWACO PSO parameters

Step 3: Initialize all the parameters and set all the required parameters

Step 4: Determine the steady state of the distribution network and obtain the candidate buses

Step 5: Ascertain the fitness of the parameters

Step 6: Investigate if all the particles fulfill the constraint otherwise, regenerate the positions of the particles

Step 7: Determine P_{best} and G_{best}

Step 8: Update the particle positions & velocity

Step 9: Draw a line between the present and historical best value. Update the variable if the present value is better than the historical value else retain Pbest as same.

Step 10: Obtain the Gbest from the Pbest values.

Step 11: Show the Gbest for AVR placement

Step 12: Obtain the comparative analysis of PSO and LSF methods with AVR placements in terms of voltage profile

Step 13: Compare the cost benefits of using PSO and LSF

Step 14: Stop

3.2 Demand side management economic evaluation.

The demand side management measures are expected to be of immense benefits to the utility, customers and in cost analysis. From the utility perspectives, it will reduce the risk of system collapse and peak demand resulting in avoided capacity additions. If the distribution codes are followed, there would be reduction in power and energy cost offered as incentives for the customers cooperation with the utility in using energy conservation technologies.

3.2.1 Benefit cost Analysis

The utility would determine the benefit to cost ratio in the following way as observed by Khedkar and Dhole (2017)

$$\text{The B/C Ratio} = \frac{\text{Avoided supply cost/kw}}{\text{Demand side management program cost /kw}} \tag{12}$$

The demand side management program in this study is taken as the two alternative ways of AVR placement for power loss reduction. According to Khedkar and Dhole, (2017): the customers' economic analysis,

$$\text{B/C ratio} = {\text{Regular (power + energy)costs}}\Big/{\text{Reduced (power + energy)costs}} \tag{13}$$

The reduced power plus energy cost is seen as demand side management strategies. To evaluate the benefit to cost ratio in Table 1, an exploit is made.

4. Results and Discussion

Steady-state analysis of the Enugu Electricity Distribution Network (EEDC) revealed that approximately 24.24% (23 out of 99 buses) of the buses exceeded the 5% voltage drop constraint. This significant percentage of weak nodes indicates that the network requires reinforcement to enhance voltage profiles and improve service quality. This study addresses this issue by optimizing the placement of Automatic Voltage Regulators (AVRs). The location and tap settings of the auto-transformers significantly impact the network's voltage and loss profiles. Analysis identified Nodes 97 and 76 as the most critical locations for optimal AVR placement. A comparative analysis of six PSO variants revealed that the ADIWACO PSO variant achieved the best results, with a standard deviation error of 0.000426. The Cost of Energy (COE) obtained through steady-state analysis, loss sensitivity approach, and ADIWACO PSO were ₦1,160,630, ₦569,840, and ₦565,231, respectively. The benefit-to-cost ratio of ADIWACO PSO and LSF were 88.2 and 77.3, respectively. These findings demonstrate the potential of demand-side management to enhance system reliability, prevent blackouts, and reduce investment in generation. The resulting energy cost savings provide a compelling incentive for customers to cooperate with utilities.

Table 2: Optimal Placement of AVR on the Radial distribution Network

	Without AVR/ Steady State	With AVR			Ranking
PSO Variant	Standard deviation error	ADIWACO		0.000426	1
		RIW		0.0689	6
		SPSO		0.00856	5
		ESIW		0.0008328	2
		LDIW		0.0078	4
		TIW		0.00412	3
Approach		Conventional method (LSF)		Proposed ADIWACO PSO	
Optimal Location and Tap setting of AVR		Feeder	Tap Set	Node	Tap Set
		Umuahia TR2 (Node 97)	+8	Umuahia TR2 (Node 97)	+10
		Obowo FDR (Node 76)	+6	Obowo FDR (Node 76)	+4
Total Active Power loss (KW)	5540KW	2720KW		2698KW	
Total Reactive Power loss KVAr	4800KVAr	2410 KVAr		2330 KVAr	
Net Savings (Naira)		Steady Sate		₦1,160630	
		LSF		₦569,840	
		PSO		₦565231	
Percentage Error in Active Power Loss Reduction		50.90%		51.30%	
Feeder	Voltage Before AVR	Umuahia TR2 (Node 97)		0.91824	
		Obowo FDR (Node 76)		0.91824	

The Enugu Electricity Distribution Company (EEDC) charges ₦209.50 per unit of energy for Band A customers, as shown in Table 2. Notably, the placement of Automatic Voltage Regulators (AVRs) on the power system yields a benefit-to-cost ratio (BCR) for loss reduction. Using an economic optimization model, the simulation program evaluates the cost of loss reduction against the investment cost for network upgrades, specifically the placement of AVRs. A cost-benefit analysis is performed to determine whether the benefits of reduced losses outweigh the increased system costs. In the simulation, kilowatt and kilowatt-hour distribution losses at various time periods are valued at the long-run marginal cost of supply from the Nigerian bulk supply system to the EEDC network. Figure 2 illustrates the simulation results, showing the variation of benefit-to-cost ratios with maximum feeder loading levels for AVR placements based on the Particle Swarm Optimization (PSO) and Loss Sensitivity Factor (LSF) algorithms.

Figure 3 illustrates the varying benefits of investing in voltage regulation, with distribution system costs increasing alongside feeder loading levels. The placement of Automatic Voltage Regulators (AVRs) using Particle Swarm Optimization (PSO) and Loss Sensitivity Factor (LSF) algorithms creates distinct network configurations, differing from the base case study distribution network. The benefits-to-cost ratios (BCRs) between these systems vary due to differences in load levels and losses, which are influenced by feeder loading patterns. Feeder loading levels significantly impact system losses, affecting the dynamics and economics of loss reduction and voltage drop mitigation. The economics of conductor loading and benefits of loss reduction are demonstrated in Figure 2. The plot reveals that high BCRs are achieved at high maximum feeder loading levels. Notably, the maximum benefits for AVR placement using either PSO or LSF techniques are realized at 100% maximum loading. However, at this loading level, PSO-based AVR placement yields a higher BCR than LSF-based placement. To provide a more detailed comparison, BCR values for PSO and LSF placements are extracted from the graph at four standard conductor loading levels: 25%, 50%, 75%, and 100%. These loading levels are based on the thermal and nameplate ratings of the feeders. The extracted values are listed in Table 3, which compares the BCRs for AVR placement using PSO and LSF algorithms. It is shown in Figure 3 that the increase in the feeder loading of the conductors gives a corresponding increase to the cost to the benefit ratio of using the optimization technique.

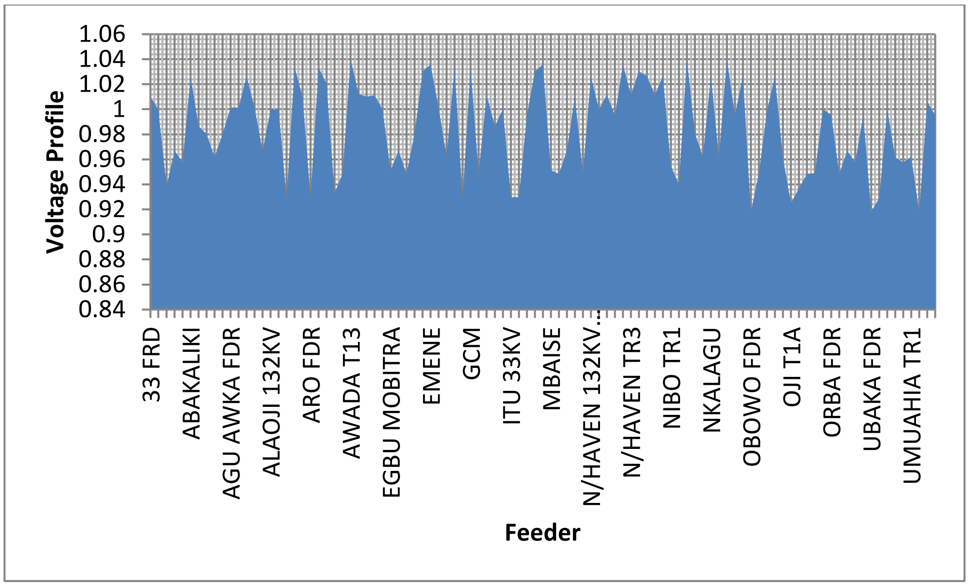

Figure 2: Voltage Profile before the installation of AVR

Table 3: Comparison of Benefit to Cost Ratio for placements of AVR based on PSO and LSF.

Maximum feeder loading (%)	BCR of AVR placement based on PSO algorithm	BCR of AVR placement based on LSF algorithm
10	2.0	1.5
20	4.5	3.2
30	5.0	4.5
40	8.5	6.0
50	9.2	8.2
60	10.5	9.0
70	11.0	10.0
80	11.5	10..5
90	12.0	11.2
100	14	13.2
Total	**88.2**	**77.3**

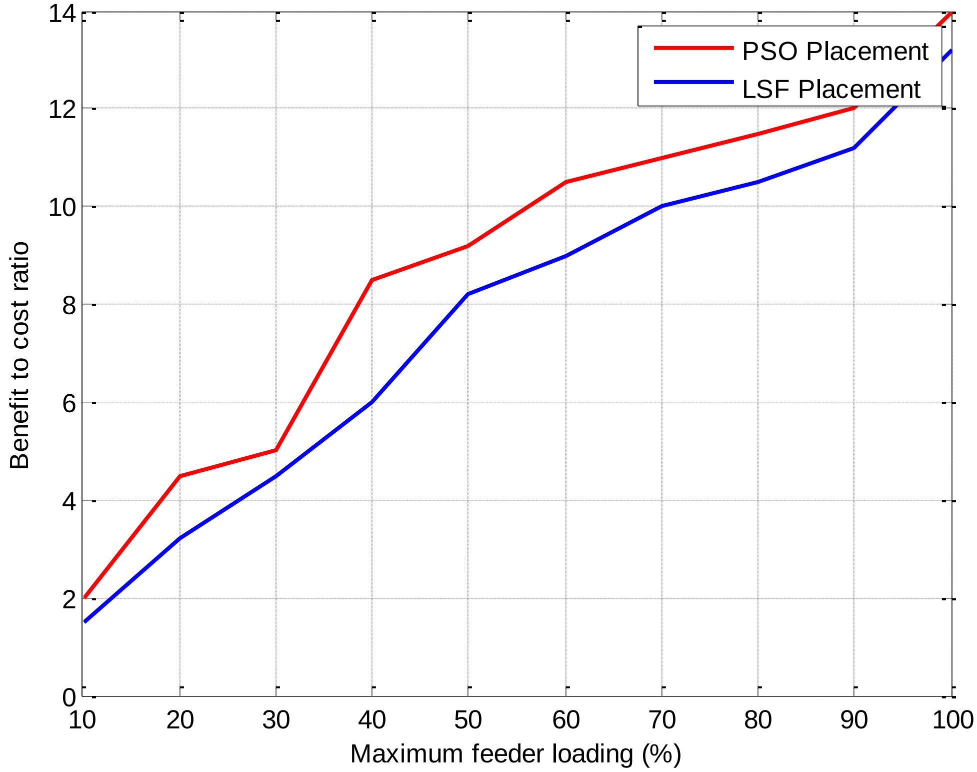

Figure 3: Comparison of the benefit-to-cost-ratios for AVRs based on the PSO and the LSF algorithms.

Table 4: Approved End-User Tariff for Enugu Electricity Distribution Company Plc (EEDC)

	Band A 20 hours and above	Band B 16 hours and above	Band C 12 hours and above	Band D 8 hours and above	Band E 4 hours and above
Non-MD	₦209.50	₦66.47	₦53.78	₦36.49	₦36.20
MD-1	₦209.50	₦62.84	₦50.21	₦47.82	₦47.60
MD-2	₦209.50	₦62.84	₦50.21	₦47.60	₦47.54

Table 3 displays the approved end-user tariff of the Enugu Electricity Distribution Company (EEDC), last updated on April 5, 2024. The tariff structure reveals that customers consuming 20 hours or more of electricity are charged a flat rate of ₦209.50 per kWh. The results indicate that EEDC can achieve savings of up to ₦209.50 for every 1 kWh of electricity consumed, provided the supply exceeds 20 hours. Under steady-state power flow conditions, the initial real power loss of 5.54 pu amounts to ₦1,160,630. In contrast, the optimal placement of Automatic Voltage Regulators (AVRs) using the Particle Swarm Optimization (PSO) algorithm yields a real power loss of 2698 kW, equivalent to ₦565,231. By reducing power losses, the equivalent load demand is decreased, potentially deferring the need for bulk system capacity additions. This, in turn, yields cost savings represented by the bulk supply. In essence, the optimal placement of AVRs via PSO can defer investments in generation and transmission (G&T) capacity expansion, freeing up resources for other areas of the power system and realizing a higher spare capacity

4.1 Voltage Profile Enhancement before and after the AVR Installation

Figure 3 shows voltage profile enhancement of 99 bus Enugu Electricity Distribution Company EEDC. So placement of AVR at Node 76 and Node 97 enhanced voltage profile as can be seen in Figure 4

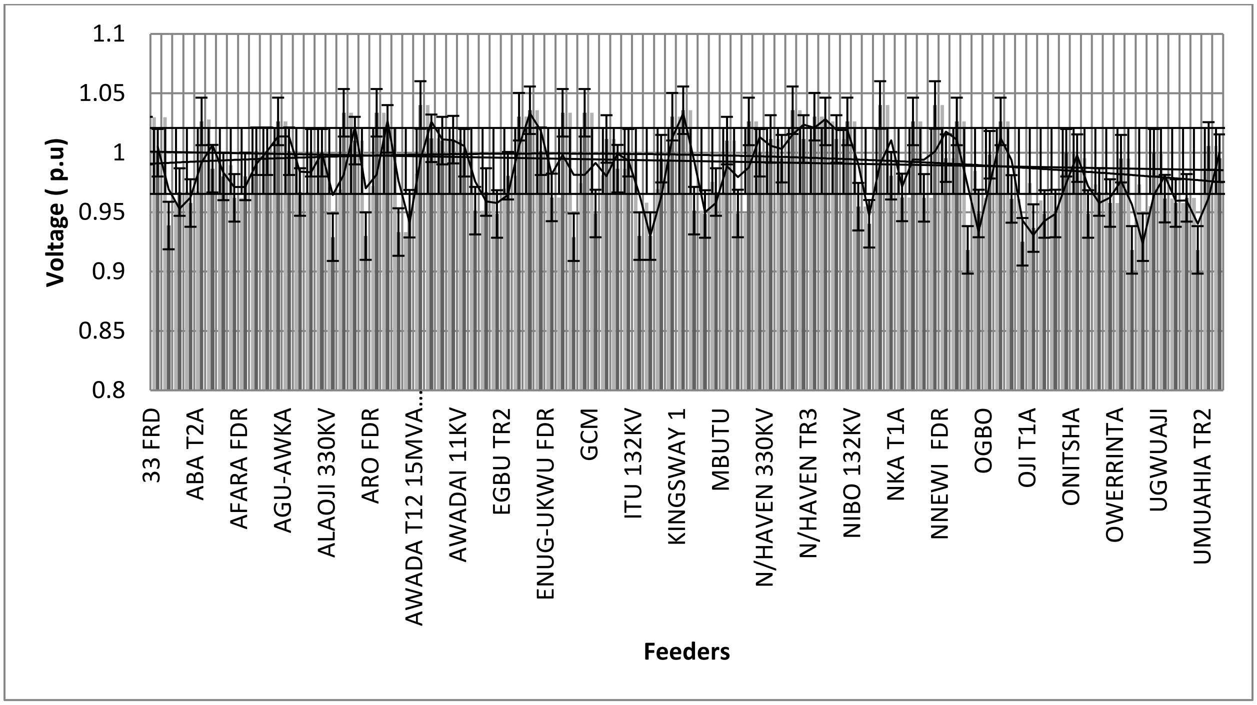

Figure 3: Voltage Profile Enhancement before and after the AVR Installation

This article makes the following key contributions to the existing body of knowledge:

i. A comparative analysis of six Particle Swarm Optimization (PSO) variants, recommending ADIWACO for its exceptional dynamic performance and tap setting of Automatic Voltage Regulators (AVRs).

ii. The development of an optimal placement strategy for AVRs using PSO, aimed at reducing power losses and enhancing voltage profiles.

iii. A comprehensive economic analysis of the loss reduction achieved through the proposed approach, providing valuable insights into the cost benefits of optimizing AVR placement."

5. Conclusion

This study introduces a novel approach to solving the Automatic Voltage Regulator (AVR) placement problem, utilizing the ADIWACO PSO algorithm. The optimal location and tap setting of AVRs were carried out thereby enhancing the voltage profile and minimization of power losses within the Enugu Electricity Distribution Company (EEDC) network. The results demonstrated significant improvements in voltage profile and substantial reductions in power losses. A comprehensive economic analysis reveals a favourable benefit-to-cost ratio (BCR) for loss reduction, underscoring the economic viability of strategic AVR placement. To attract necessary investment and upgrade existing infrastructure, it is recommended that Distribution Companies (DISCOs) consider deregulating loss minimization. This would enable third-party investment in loss reduction and voltage profile enhancement services, driving improvements in overall efficiency and reliability. Again, if the national distribution code is implemented, all the stake holders in the power sector would wake up to their responsibilities.

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