Optimized Electric Power Distribution via Genetic Algorithm Based Estimation

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Abstract — **Power losses will always occur during the distribution of electricity, no matter how carefully distribution lines are designed. Cutting out these losses in lines to a minimal level will improve the efficiency of the supply of electricity and also add financial and economic value to the host nation. This research shows an effective way of minimizing power loss in distribution lines using optimal capacitor placement (OCP) in conjunction with a genetic algorithm (GA). The Electrical Transient Analyzer Program (ETAP) was used for simulation with the Choba 11kV feeder as a case study. The load flow analysis carried out using the Newton-Raphson method showed that 67 out of the 76 buses were critically and marginally loaded, leading to a low voltage profile below the IEEE-prescribed limit of ±5%. To improve the performance of the entire network and minimize losses, the GA powered OCP model on ETAP strategically deployed appropriate reactive power through capacitor banks at its best location. The load flow results after enhancement showed an improved voltage profile, and the losses in the network were significantly reduced to the tune of 12% reduction, with a huge annual profit of from the second year. Cumulatively, the expected total capacitor operational cost, loss reduction savings, and profit for the planning period are $58,000, $304,323.5, and $83,523.46, respectively.**

***Index Terms*—Distribution feeder, genetic algorithm, optimal capacitor placement, power loss.**

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I. INTRODUCTION

Electrical power is basically one of the most important forms of energy in the world. It is very essential for every home, industry, or business to have access to electricity because almost every gadget, appliance, or even work activity requires the use of electricity. And as a result, the demand for power supply has increased greatly over the years.

The Nigerian power sector feeds almost the entire country and some neighboring countries in West Africa. Distribution stations supply power from the transmission stations to consumers. In practice, long 11 kV distribution lines in rural areas are usually set up over long distances to feed consumers in scattered settlements. This lengthy radial line over long distances leads to high line resistance, which results in copper or electric (I^2R) losses.

No matter how distribution lines are carefully designed, losses are always encountered every now and then [1]. The purpose of this research is to find an effective way in which these losses in distribution lines can be ascertained and reduced to a minimal level, as much as possible.

Distribution line loss reduction has been an area of interest to many researchers. Many researchers have used different methods to ascertain the state of losses in the network. Such methods include Newton-Raphson [2–3], Gauss-Seidel [4], etc. Recent approaches often use AI-based algorithms, as can be seen in [5–9]. Decongestion of the line network is the first line of action. Some distribution network operators perform reconfiguration of the line network [10] and load balancing of the transformers [11–12] to reduce losses. In some cases, there will be a need to add a new injection substation in order to reduce losses in the existing network [13]. The use of relief transformers to improve the loss of affected lines is a common practice [14].

Another approach to loss reduction in the distribution network is the addition of capacitor banks [15–17] and other compensators [18] to specific buses to improve the bus voltage profile. Also, distributed generation sources have been used to improve the network [19–20].

The Egbema clan distribution network [21] was considered with the sole aim of improving power distribution through the allotment of appropriate capacitor banks but failed to accommodate cost implications for the optimization model. This research is aimed at sophisticating the optimization model implemented in [21] through the incorporation of cost analysis for a ten-year period using the Choba 11kV distribution network.

II. METHOD

The Newton-Raphson method of load flow analysis has a very good convergence rate, and it is highly dependent on the bus voltage initial values. When the initial values of the bus voltage are significantly different from their true values, convergence becomes difficult. Thus, a careful selection of the initial values of bus voltage is highly recommended.

Before the Newton-Raphson method is used for load flow analysis, ETAP makes a few Gauss-Seidal iterations to establish a set of sound initial values for the bus voltages. The Newton-Raphson method is particularly suited for large systems which would have required large computer time.

The Newton-Raphson method of solving the load flow problem using equations (1) to (9) is based on the Taylor's series expansion for a function of two or more variables. At any bus K , P_k and Q_k into the system of N buses are given by [4]:

$$P_K - jQ_k = \sum_{n=1}^{N} Y_{kn}V_k \quad (1)$$

$V_k and Y_{kn}$ are complex and can be expressed as:

$$V_k = a_k + jb_k \quad (2)$$

$$Y_{kn} = G_{k_n} - jB_{k_n} \quad (3)$$

Substituting equations (2) and (3) into (1).

$$P_K - jQ_k = (a_k - jb_k)\sum_{n=1}^{N}(G_{kn} - jB_{kn})\,(a_n + jb_n) \quad (4)$$

At the voltage – controlled buses (say bus p), the square of the voltage magnitude is given as:

$$|V_P|^2 = a_p^2 + b_p^2 \quad (5)$$

$P_k$and $Q_k$are the real power and reactive power of the bus.

The incremental values of these powers are given as:

$$\Delta P_k = P_k \text{ (specified) - } P_k \text{ (calculated)} \quad (6)$$

$$\Delta Q_k = Q_k(specified) \text{ - } Q \text{ (calculated)} \quad (7)$$

$$|\Delta V_k|^2 = |V_K(specified)|^2 - |V_k(calculated)|^2 \quad (8)$$

Considering the same matrix below:

$$\left[\frac{\Delta P}{\Delta Q}\right]\begin{bmatrix} J_1 & J_2 \\ J_2 & J_4 \end{bmatrix} = \left[\frac{\Delta\delta}{\Delta V}\right] \quad (9)$$

The elements of the Jacobean are found by taking the partial derivatives of the expressions of P_k andQ_k, and substituting the voltages assumed for the first iteration.

The Newton – Raphson technique can be summarized as [4]:

i. For the first, voltage obtained by Gauss-seidal iteration are used to calculate P_k and $Q_k$or $|V_K|^2$ (except when k = 1)

ii. Determine ΔP_k and ΔQ_k or $|\Delta V_k|^2$ $e$xcept when k = 1) from equations (3.6) to (3.8), and compare with the precision index. If the three quantities are all less than the precession index, stop iteration, calculate P_1 and Q_1 and print the entire solution.

iii. If the precision index has not been met, evaluate the elements of the Jacobian by substituting in the expressions for the partial derivatives

iv. Solve equation (3.9) for Δa_k and b_k (except when k = 1)

v. Determine new bus voltage by adding the voltage changes to the previous values.

vi. Return to step 1.

Optimal capacitor placement (OCP) deals with the determination of the location, size and number of capacitors infested in the distribution system, in order to obtain the best option at the different head levels. The main reason of using the capacitors in distribution networks is to minimize the total losses on the given network. An optimization algorithm decides the location of the nodes where the capacitors should be placed [14].

After load flow analysis was carried out on the network under investigation, OCP was carried out to systematically improve the current state of the network with inclusion of cost implications for implementation using equation 10 [13].

$$\sum_{i=1}^{N_{bus}}(x_iC_{0i} + Q_{ci}C_{1i} + B_iC_{2i}T) + C_2\sum_{l=1}^{N_{load}} T_lP_L^l \quad (10)$$

Where;

N_{bus}- Number of bus candidates

x_i – 0/1, 0 means no capacitor at bus i

C_{0i} – Installation cost

C_{1i} – Per $kVar$ cost of capacitor banks

Q_{ci} – Capacitor bank size in $kVar$

B_i – Number of capacitor banks

C_{2i} – Operation cost of per bank yearly

T – Planning period

C_2 – cost of each KWh in \$/ KWh

l – load levels

T_i – Time duration

P_L^l – Total system loss at load level

The step by step procedure for optimal capacitor placement through genetic algorithm is contained in the flow chart as shown in Fig. 1.

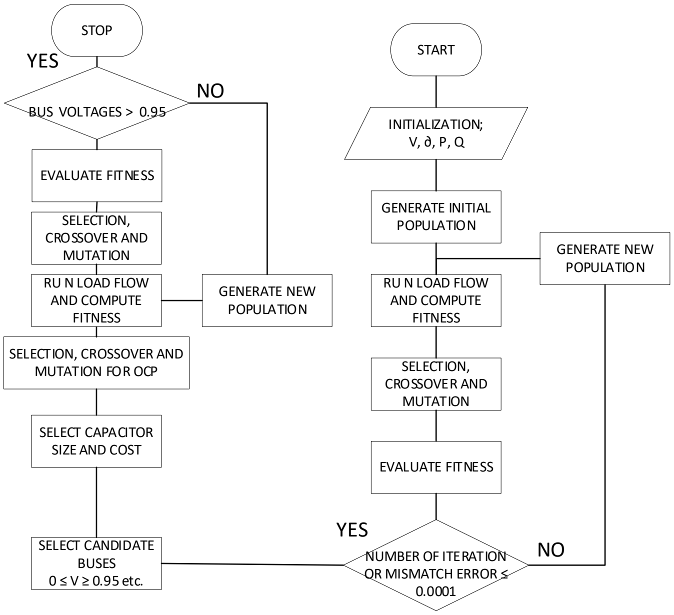


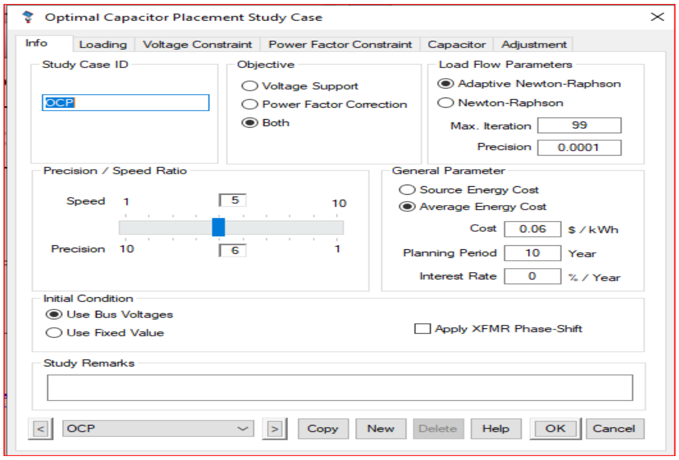
Fig.1. Genetic Algorithm Implementation Flow Chart [15].

Electrical transient analyser program (ETAP) was used for network design and simulation. First, load flow study is being conducted on the designed network to ascertain the existing conditions of the 11kv feeder. Based on the power flow result, voltage and power factor constraints are been set in line with IEEE regulations. To enable the genetic algorithm (GA) perform optimally, candidate buses are identified based on the violation report from the load flow. Finally, adequate capacitors are chosen based on the network nominal voltage for effective sizing and allocation. Pictorially, these steps are shown in Fig.2a, 2b, 2c and 2d, respectively.

Summarily, the implementation procedure entails conducting a load flow study using Newton Raphson solution, identifying and selection candidate buses, estimation of reactive power and finally allotment of reactive to suitable busbars for optimal loss minimization through voltage profile improvement subject to the following constraints.

$$0.95 \le V \ge 1.05 \tag{11}$$

$$0 \le Q \ge 5.8\,Mvar \tag{12}$$



Study Case ID: OCP

Objective
○ Voltage Support
○ Power Factor Correction
● Both

Load Flow Parameters
● Adaptive Newton-Raphson
○ Newton-Raphson
Max. Iteration: 99
Precision: 0.0001

Precision / Speed Ratio
Speed: 1 – 5 – 10
Precision: 10 – 6 – 1

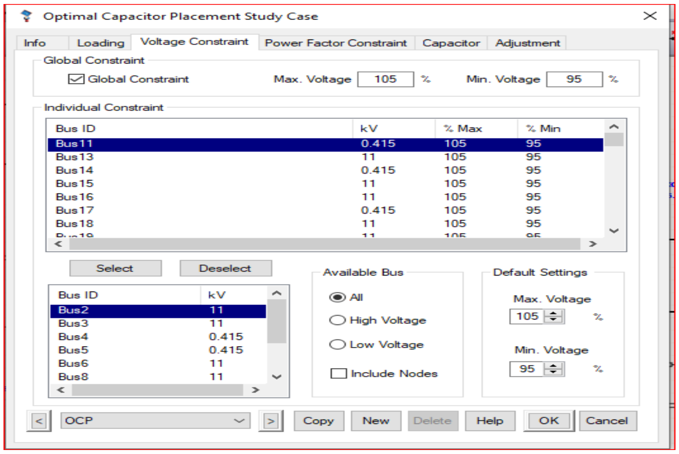
General Parameter
○ Source Energy Cost
● Average Energy Cost
Cost: 0.06 $ / kWh
Planning Period: 10 Year
Interest Rate: 0 % / Year

Initial Condition
● Use Bus Voltages
○ Use Fixed Value
☐ Apply XFMR Phase-Shift

Study Remarks

OCP

Fig.2a. OCP Information Window in ETAP.



Global Constraint
☑ Global Constraint   Max. Voltage 105 %   Min. Voltage 95 %

Individual Constraint

Bus ID	kV	% Max	% Min
Bus11	0.415	105	95
Bus13	11	105	95
Bus14	0.415	105	95
Bus15	11	105	95
Bus16	11	105	95
Bus17	0.415	105	95
Bus18	11	105	95

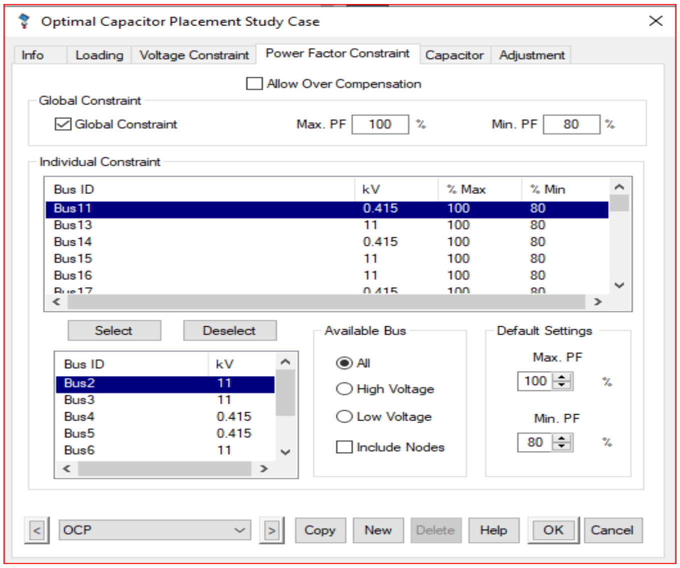
Bus ID	kV
Bus2	11
Bus3	11
Bus4	0.415
Bus5	0.415
Bus6	11
Bus8	11

Available Bus
● All
○ High Voltage
○ Low Voltage
☐ Include Nodes

Default Settings
Max. Voltage 105 %
Min. Voltage 95 %

OCP

Fig.2b. OCP Voltage Constraint Window in ETAP.



☐ Allow Over Compensation

Global Constraint
☑ Global Constraint   Max. PF 100 %   Min. PF 80 %

Individual Constraint

Bus ID	kV	% Max	% Min
Bus11	0.415	100	80
Bus13	11	100	80
Bus14	0.415	100	80
Bus15	11	100	80
Bus16	11	100	80

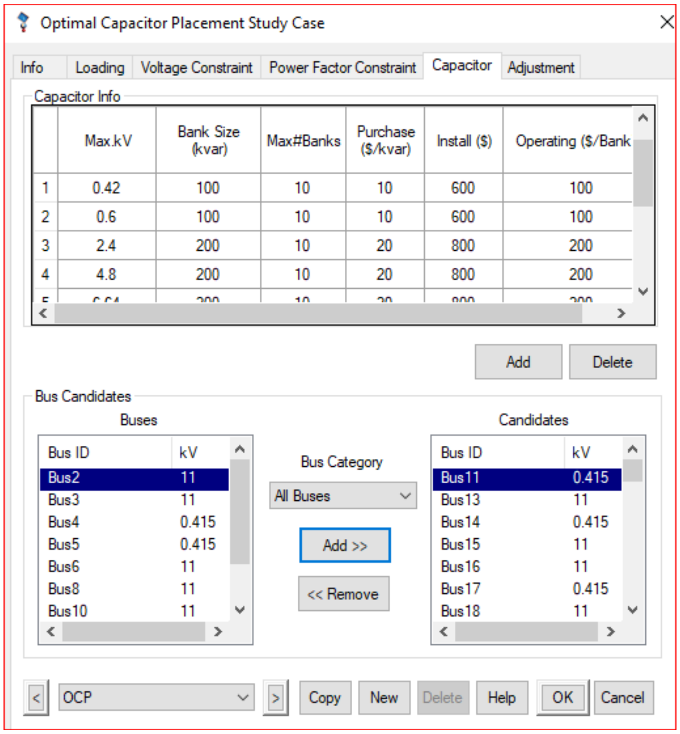
Bus ID	kV
Bus2	11
Bus3	11
Bus4	0.415
Bus5	0.415
Bus6	11

Available Bus
● All
○ High Voltage
○ Low Voltage
☐ Include Nodes

Default Settings
Max. PF 100 %
Min. PF 80 %

OCP

Fig.2c. OCP PF Constraint Window in ETAP.



Capacitor Info

	Max.kV	Bank Size (kvar)	Max#Banks	Purchase ($/kvar)	Install ($)	Operating ($/Bank
1	0.42	100	10	10	600	100
2	0.6	100	10	10	600	100
3	2.4	200	10	20	800	200
4	4.8	200	10	20	800	200

Bus Candidates

Buses

Bus ID	kV
Bus2	11
Bus3	11
Bus4	0.415
Bus5	0.415
Bus6	11
Bus8	11
Bus10	11

Bus Category

Candidates

Bus ID	kV
Bus11	0.415
Bus13	11
Bus14	0.415
Bus15	11
Bus16	11
Bus17	0.415
Bus18	11

Fig.2d. OCP Capacitor Window in ETAP.

III. RESULTS AND DISCUSSION

From the data collected, both main network and composite networks together, comprises of seventy-six buses, thirty loads, zero generators, and one power grid.

The result displayed in Fig.3a clearly shows the current state of the network before optimal capacitor placement (OCP). Twelve of the eighteen buses in Fig.3a are marginally overloaded, which means the voltage drop is still within the ±5% IEEE voltage regulation. Only bus 17 is critically overloaded, which results in under voltage, as it is below the -5% IEEE voltage regulations. The red and pink colors indicate respectively, how critical and marginal the voltage drop at the buses are, with reference to the IEEE voltage regulation.

The results in Fig.3b shows that 31 of the 33 buses are critically overloaded resulting to a voltage below the -5% IEEE voltage regulation while the excluded two buses, 19 and 21 are marginally overloaded. The result in Fig.3c shows that 17 of the 25 buses are critically overloaded while the remaining 8 buses are marginally overloaded.

The existing state of the 76-bus network investigated is largely overloaded in the critical domain resulting to 55.25% voltage drop and $0.19MW + j0.276Mvar$ real and reactive power loss.

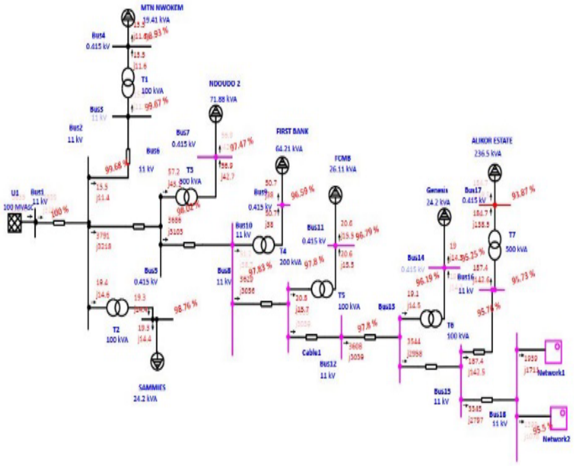


Fig.3a. Load Flow Simulation Result of Choba 11kV Distribution Network before OCP.

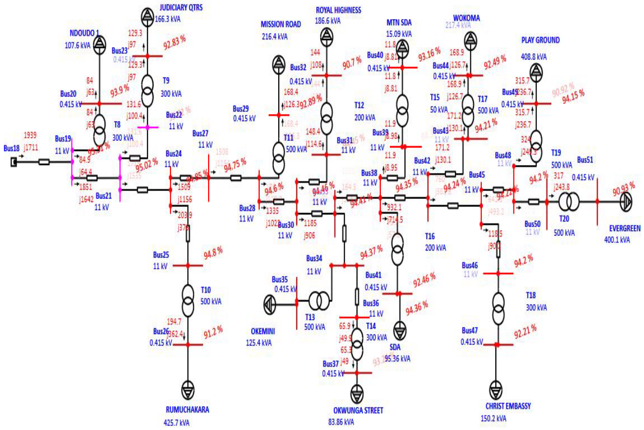


Fig.3b. Load Flow Simulation Result of Composite Network 1 before OCP.

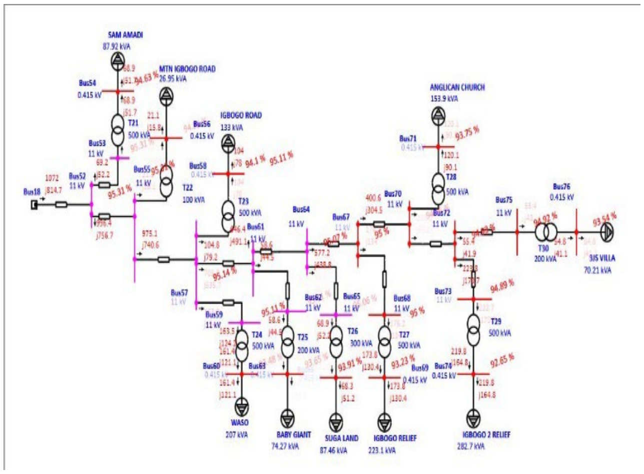


Fig.3c. Load Flow Simulation Result of Composite Network 2 before OCP.

As we look to minimize power losses and consequently improve the performance of the entire network, capacitors of appropriate sizes were suggested at strategic locations in the network, using Genetic Algorithm (GA). The results after optimal capacitor placement (OCP) estimated a maximum of 5.8Mvar as the required amount of reactive power needed for improvement of the system. Evidently, after injecting 13 banks of $400kvar$ each at bus 18 amounted to a total injection value of $5.2Mvar$ which is less than the maximum reactive power value proposed. The obtained result showed improved voltage profile, reduced power loss and voltage drop and an optimized power flow.

The post OCP result as contained in Fig.5 and 6 vindicates the efficacy of the deployed algorithm as the power losses were drastically reduced from $190kW + j276kvar$ to $168kW + j0.243kvar$ due to voltage profile improvement from critical to a minimum of marginal and reduction in voltage drop from 55.25% to 50.17%.

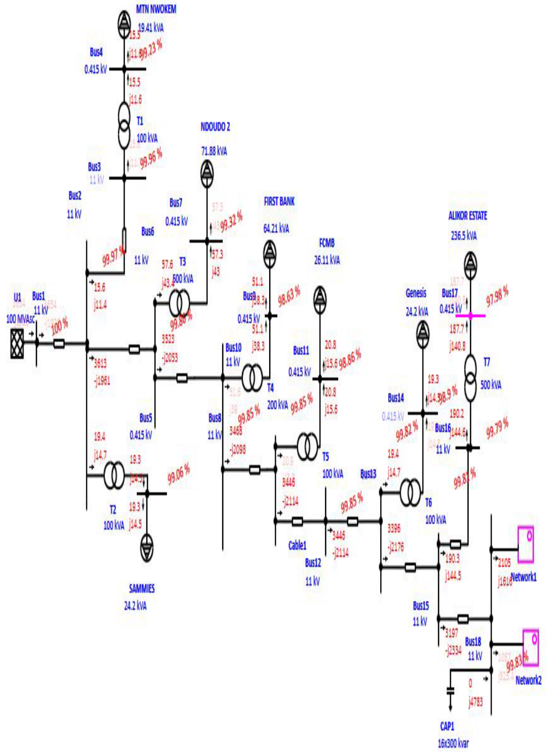


Fig.4a. Load Flow Simulation Result of Choba 11kV Distribution Network after OCP.

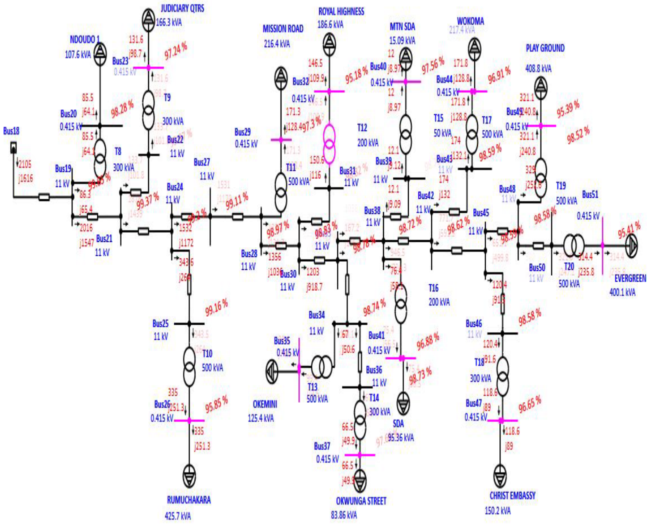


Fig.4b. Load Flow Simulation Result of Composite Network 1 after OCP.

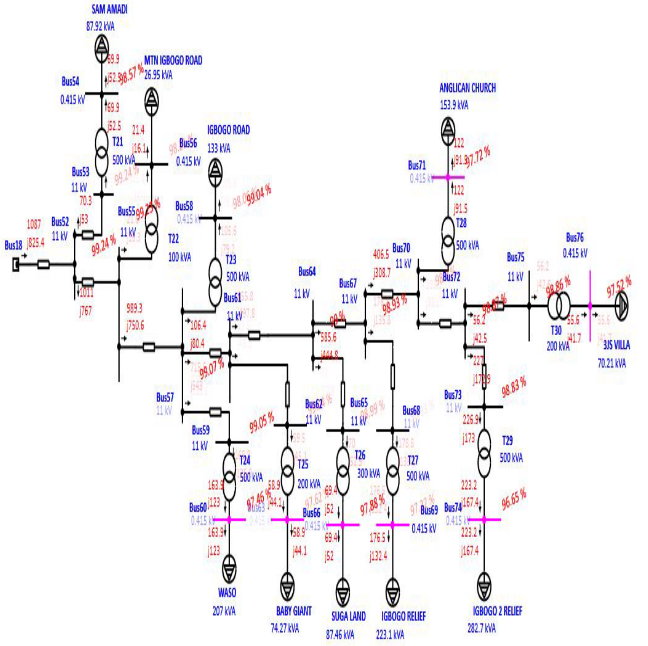


Fig.4c. Load Flow Simulation Result of Composite Network 2 after OCP.

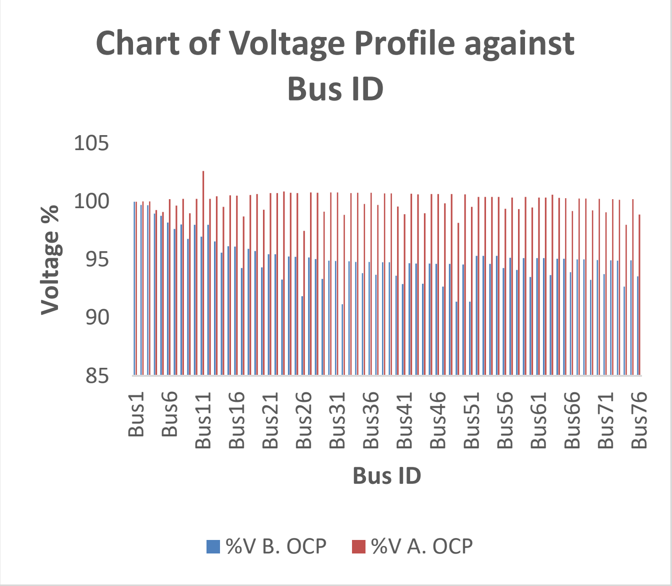


Fig.5. Bus Voltage Profile before and after OCP.

In Fig. 5, the percentage bus voltage profile before and after improvement is being presented for the 76-bus network. Out of the 76 buses, 26 buses are marginally overloaded, 9 buses are good and 41 buses are critically overloaded resulting to huge amount of voltage drop and power loss.

The post-OCP result is a huge improvement of the pre-OCP result, as all critically loaded buses were successfully transformed to good and slightly marginal buses. Out of 76 buses, after injection of reactive power through optimal placement of capacitor banks at appropriate busbars, 74 buses gained good status while 2 buses were marginal in conformity with the IEEE statutory voltage drop requirement.

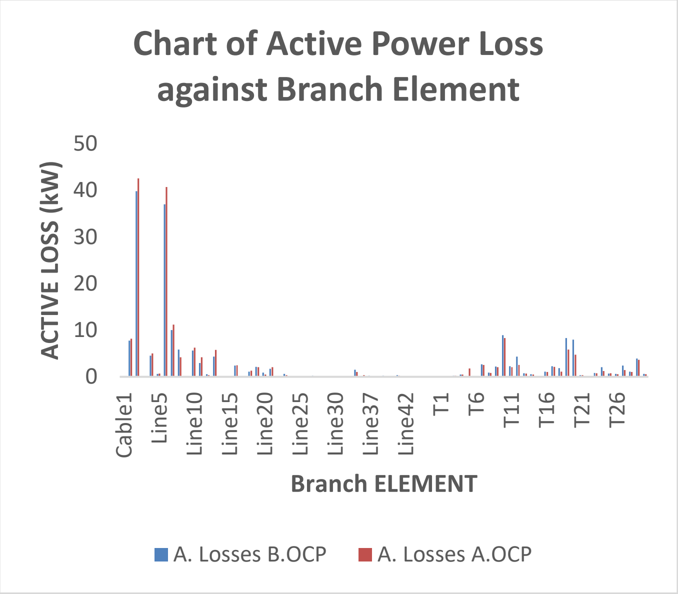


Fig.6. Load Flow Result of Active Power Loss before and after OCP.

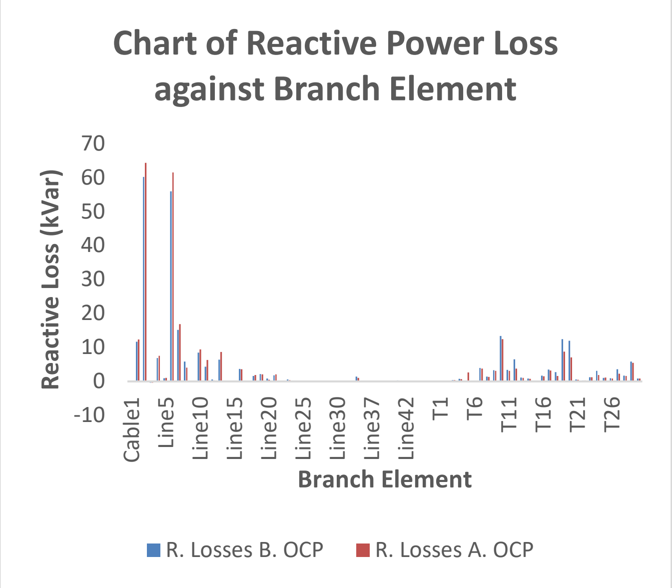
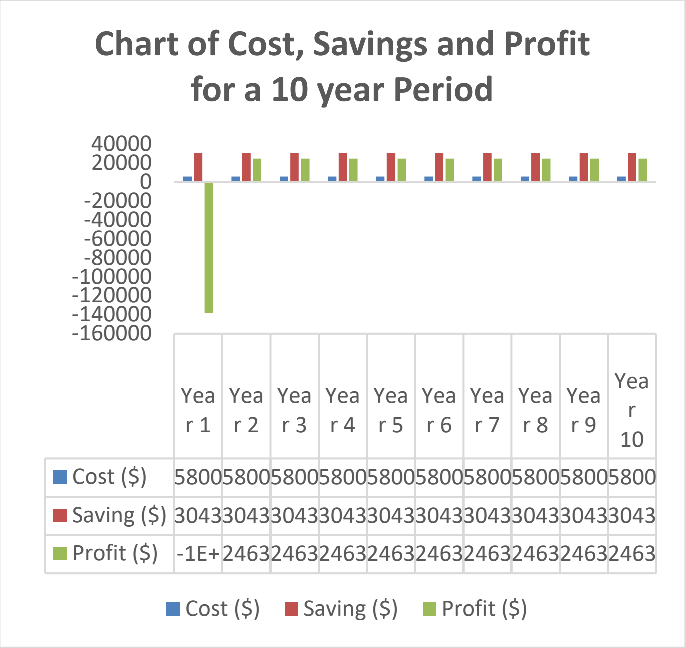


Fig.7. Load Flow Result of Reactive Power Loss before and after OCP.

The active power loss contained in Fig. 6 validates the voltage profile results shown in Fig. 5. A total of 190kW was recorded as active power loss in the pre-OCP simulation against a total of 168kW in the post-OCP simulation. The pre and post-OCP losses are denoted by the blue and orange legend respectively. Similarly, the reactive power loss after pre and post-OCP simulations are contained in Fig. 7. A total of $276\ and\ 243kvar$ were recorded as the total reactive power losses before and after network optimization.



	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Cost ($)	5800	5800	5800	5800	5800	5800	5800	5800	5800	5800
Saving ($)	3043	3043	3043	3043	3043	3043	3043	3043	3043	3043
Profit ($)	-1E+	2463	2463	2463	2463	2463	2463	2463	2463	2463

Fig.8. Cost Analysis Report for a Ten-Year Period.

The cost implication for optimal power loss reduction and voltage profile improvement via optimal allotment of capacitor banks is conspicuously showed in Fig. 8. The cost of implementing the proposed solution on the Choba 11kV distribution network is small compared to the benefit it offers the concerned electricity service providers and consumers. The cost analysis of implementation was considered in light of operation, loss reduction and profit for a ten-year period.

Numerical results as contained in Fig. 8 show that a total of $5800 will be expended annually as operational cost whereas a profit of $24,632.35 will be realized annually by the second year and maintained throughout the ten years as a result of ample power loss reduction. Cumulatively, the expected profit value for the planning period will be $83,523.46 whereas the expected savings due to loss reduction will be $302,323.5 for the planning period.

VI. CONCLUSION

This study describes the theoretical and practical issues concerning power loss minimization in electric power network, using capacitor placement as one of the numerous methods of loss reduction. After load flow analysis was carried out on Choba 11kV distribution network, the results showed that the percentage voltage magnitude of the buses and the percentage voltage drop of the branch elements of the network were below the recommended ±5% limit stipulated by the IEEE. And the active and reactive power losses were 0.19MW and 0.276Mvar.

In order to effectively improve the network voltage profile, and consequently minimize the power losses in the network, Optimal Capacitor Placement (OCP) was employed. Capacitor banks to the tune of 5200kvar were carefully placed at bus 18 and the yielded results was positive with regards to network and power quality improvement. The results after OCP, showed that the active and reactive power losses in the network were significantly minimized to 0.168MW and 0.243Mvar.

Careful consideration of the power loss value after OCP implementation, it is evident that the proposed solution algorithm is cost-effective and profitable to both distribution companies and electricity consumers as power availability and stability is maximized as well as productivity which is profitable for all parties.

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