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Optimal Sizing and Allocation of Reactive Power Agents for Improved Distribution

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Abstract— Reactive power agents such as shunt capacitors and inductors are deployed for the purpose of reactive power injection or absorption during heavy or light loading of load feeders for power loss reduction through optimization of voltage profile. In this research, a multi-objective Tabu Search Algorithm (TSA) is being deployed for optimal allotment and sizing of capacitor banks in a 21 bus 132/33kV Port Harcourt Sub-Transmission and Primary Distribution Network. The proposed algorithm was implemented in DigSILENT Power Factory 15.1 and the results were validated by comparison with the existing network state through load flow studies. Both the pre-OCP and post-OCP load flow simulation results were critically analysed and emanating results showcased the efficiency of the Tabu Search Algorithm in power loss reduction. The power loss before and after placement of 70 capacitor banks; each rated 0.96MVAR across seven load buses were recorded as 10.54MVAR and 8.7MVAR respectively. This loss index represents a 17.5% loss reduction and further vindicates the algorithm in efficacy and accuracy.

Indexed Terms— Optimal, Allocation, Reactive, Power, Agents, Improved, Distribution, Voltage, Tabu, Search, DigSILENT.

I. INTRODUCTION

Reactive power is generated or absorbed in power networks by shunt capacitors or reactors to cushion the effect of or completely mitigate voltage dip and rise. Before the advent of artificial intelligence (AI) solution algorithms, traditional methods of trial and error and sensitivity analysis were predominantly used for capacitor sizing and placement.

This research was able to achieve a stable and reliable power system through adequate power flow and minimized power loss through injection of adequate and appropriate banks of capacitor or inductor depending on the outcome of the load flow analysis report.

Newton Raphson (NR) method is used for system load flow analysis and based on the outcome an artificial intelligence-based solution algorithm called Tabu searched is adopted for optimal sizing and allotment of reactive power agents to maintain voltage profile within the IEEE ±5% statutory voltage regulation.

The distribution network investigated is a secondary distribution feeder in the Port Harcourt metropolis under the management of Port Harcourt Electricity Distribution Company (PHEDC). The 33kV radial distribution feeder will be remodelled and simulated in power flow mode to ascertain the real and reactive power flow, level of power mismatch, losses, voltage magnitude and phase angle in DigSILENT PowerFactory 15.1 software. The outcome of the load flow will determine whether reactive power is to be generated or absorbed.

The extent of reactive power to be generated or absorbed and its distribution across the feeder for optimal solution will be revealed upon successful implementation of the proposed algorithm.

II. LITERATURE

Extensive literature review was conducted in the artificial intelligence solution domain during the formative process of this research. Detection and sizing of unified power flow controllers (UPFC) and thyristor-controlled series controllers (TCSC) FACTs devices for transmission losses minimization was achieved using genetic algorithm-based solution technique. [1]

Similarly, GA was deployed for optimal sizing and allotment of capacitor banks for improved power distribution. [2]

Particle swarm optimization (PSO) was hybridized with GA for effective power loss minimization while PSO in stand-alone mode was deployed for optimal sizing and allocation of distributed generation. [3-5] The problem of optimal reactive power dispatch was solved using a modified salp swarm algorithm (MSSA) for optimal allocation of static synchronous series compensator (SSSC). [6]

Improved harmony search algorithm (IHSA) was used to improve voltage profile and minimize power loss through adequate sizing and allotment of static var compensators (SVC). [7]

[8-9] considered feeder configuration and optimal sizing of capacitor banks and distributed generation as appropriate means of power flow improvement with the aid of two AI solution algorithms called quasi-reflection-based slime mold algorithm (QRBSA) and meta-heuristic grasshopper optimization algorithm (MGOA).

Autonomous group particle swarm optimization (AGPSO) was evolved in [10] for network reconfiguration and optimal capacitor placement for power system loss reduction through voltage control. Extensive review was conduction on major AI based solution techniques with the aim of analyzing performance in single and multi-objective domain. [11]

III. MATERIALS AND METHOD

Aside the literatures sourced online, relevant power system network data inclusive of single line diagram were obtained from Transmission Company of Nigeria and Port Harcourt Electricity Distribution Company for proper representation and description of the primary distribution feeder under scrutiny.

The data gathered clearly describes the 132kV sub-transmission and 33Kv primary distribution feeder as a 21-bus, 15 transformer and 11 feeder network with a cumulative real and reactive load of $390.6MW$ and 293.326 MVAR. Summary of the data garnered are displayed in Table 1.

Table 1: 132/33 kV Network Data

S/N	TRF. UNIT	TRF (MVA)	LOAD (MW)	LOAD (MVAR)
1	2	40	40	30
2	2	40	47	35.25
3	1	60	36.1	27.08
4	1	60	32.2	24.15
5	1	60	48	36
6	2	40	31	23.25
7	2	60	63.8	47.85
8	1	30	22.3	16.723
9	1	45	22.3	16.723
10	1	60	28	21.4
11	1	30	19.9	14.9

The data gathered clearly describes the 132kV sub-transmission and 33Kv primary distribution feeder as a 21-bus, 15 transformer and 11 feeder networks with a cumulative real and reactive load of $390.6MW$ and 293.326 MVAR. The system under investigation is shown in Figure 1.

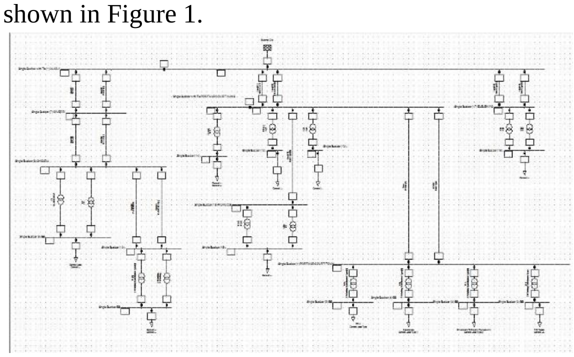

Figure 1: 132/33kV Sub-Transmission and Primary Distribution Network

The system represented in figure 3.1 is designed and analysed in DigSILENT Power Factory 15.1 and all sub-transmission feeders are classified as short lines ranging between 1 to 80kM.

B. METHODS

The load flow fundamental equations are being implemented assuming an N-bus network carrying supply from bus i to bus k. The current received at bus i from the generator or power grid is given as;

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + .. + Y_{ik}V_K = \sum_{i,k=1}^{n} Y_{ik}V_k \quad (1)$$

Considering magnitude and phase angle, the voltage and admittance will be given as;

$V_k = V_k < \delta_k$ (Voltage at the bus k) (2)

$Y_{ik} = Y_{ik} < \theta_{ik}$ (3)

Substitute equations (2) and (3) into equation (1)

$I_i = \sum_{i,k=1}^{n} Y_{ik} < \theta_{ik}\ V_k < \delta_k$ (4)

δ_i, δ_k are phase angles of bus i and k, while θ_{ik} is the angular difference between bus i and k.

Conjugate of the injected current at bus i will be;

$I_i^* = \sum_{i,k=1}^{n} Y_{ik} < -\theta_{ki} V_k < -\delta_k$ (5)

Apparent power available at bus i will be;

$S_i = V_i I_i^* = P_i + jQ_i$ (6)

Substitute equation (5) into equation (6), considering the magnitude and angle of V_i

We have;

$P_i + jQ_i = V_i < \delta_i \sum_{i,k=1}^{n} Y_{ik} < -\theta_{ki} V_k < -\delta_k$ (7)

Rearranging equation (7) gives;

$P_i + jQ_i = \sum_{i,k=1}^{n} Y_{ik} V_i V_k < (-\theta_{ki} + \delta_i - \delta_k)$ (8)

But,

$\delta_{ik} = \delta_i - \delta_k$ (9)

$-\theta_{ki} = \theta_{ki}$ (10)

Substitute the relations in equations (9) and (10) into equation (8)

$P_i + jQ_i = \sum_{i,k=1}^{n} Y_{ik} V_i V_k < (\theta_{ki} + \delta_{ki})$ (11)

From the equation (11), the active real and imaginary power will be;

$P_i = \sum_{i,k=1}^{n} Y_{ik} V_i V_k \cos(\theta_{ki} + \delta_{ki})$ (12)

$Q_i = \sum_{i,k=1}^{n} Y_{ik} V_i V_k \sin(\theta_{ki} + \delta_{ki})$ (13)

Equations (12) and (13) are used to obtain calculated values of real and reactive power.

Note that if a bus generates electricity, it is called an electric bus other than the bus loading; a loose bus is also needed to install (suction) excess flow. Line flow may also be expressed as changes in the bus and / or generator capacity generated by the computer in relation to the previously stated bus and / or generator values and are defined as follows:

$\Delta P_i = \left|P_i^{sp} - P_i^{cal}\right|$ (14)

Where,

$P_i^{sp} =$ the specified real bus powers at power exchange sequence i, and

$P_i^{cal} =$ the computed real bus powers at power exchange sequence i, using equation 12

Similarly, the reactive power changes may be expressed as:

$\Delta Q_i = \left|Q_i^{sp} - Q_i^{cal}\right|$ (15)

Where,

$Q_i^{sp} =$ the specified reactive bus powers at power exchange sequence i, and

$Q_i^{cal} =$ the computed reactive bus powers at power exchange sequence i, using equation 13.

Typically, the admittances, line power demand and generations are given while the bus voltages and angles are obtained by making an initial guess and solving using a load-flow program.

The net power balance is then expressed as the sum over all bus power sequence exchanges as:

$\Delta P_{net} = \Sigma_i^n \Delta P_i^2$ (16)

and,

$\Delta Q_{net} = \Sigma_i^n \Delta Q_i^2$ (17)

Equations 1 to 17 are the fundamental power flow equations and its solution is facilitated using the traditional Newton Raphson solution algorithm [12].
The Newton-Raphson method holds and repeatedly solves the following flow rate:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \quad (18)$$

Where ΔP and ΔQ are the actual bus power and the operating force do not exactly match the vectors between the stated value and the calculated value, respectively; ΔV and Δδ represent the maximum power of the bus and angles in the form of additions; and J1 to J4 are called Jacobean matrices. [2]

Tabu search is an optimization methodology that guides a local heuristic search procedure to explore the solution space beyond local optimality. It is substantiated by the hypothesis that an intelligent solving algorithm must incorporate memory to base its decisions on information collected during the search. The method creates in this way a learning pattern to explore the solution space economically and effectively. Tabu search is a meta-heuristic that has proved its effectiveness in a wide variety of problems, especially in combinatorial optimization. [13]

The choice of algorithm was informed by its computational strength in terms of accuracy and efficacy which out-weighs its poor computational speed. In this research, the Tabu search algorithm

(TSA) is adopted for optimal sizing and placement of capacitor banks for power loss reduction and cost minimization. This can be achievement through an objective equation as contained in equation 19.

$$\text{Total costs} = C_{Losses} + \sum_{i=1}^{m} Ccap_i + \sum_{i=1}^{n} C_{voltvioli} \quad (19)$$

Where;

$C_{Losses} =$ annual cost of grid loss

$Ccap_i$ = annual operational cost of capacitor (m is the number of capacitors installed)

$C_{voltvioli} =$ fictitious cost used to penalize a bus voltage violation (n is the number of bus terminals with voltage violations)

Through the objective equation, the TSA is able to perform a loss sensitivity analysis (LSA) for identification of appropriate candidate buses and subsequent ranking of terminals in descending order starting with the largest loss reduction terminal down to the lowest terminal with the aim of identifying the best candidate bus. Upon identification of the candidate bus or buses, suitable capacitor sizes according to available are allotted optimally for effective power loss reduction. The procedural implementation of the meta-heuristic algorithm is seen in Figure 2.

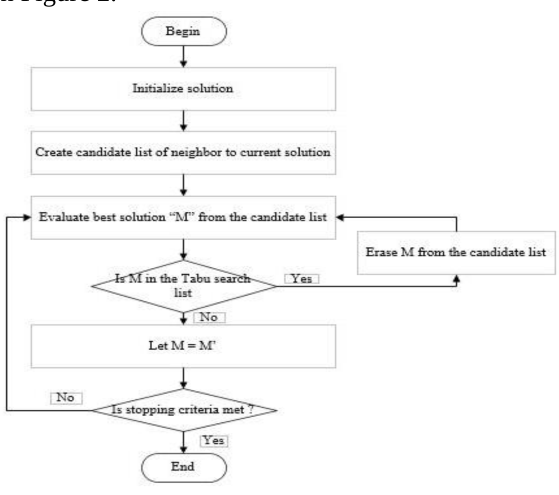

Figure 2: Tabu Search Procedural Chart [14]

The flowchart clearly explains the step by step implementation of the TSA as embedded in the DigSILENT Power Factory environment. The efficacy of the simulation results will be examined in the next chapter with critical focus on the power loss index before and after optimal capacitor placement.

IV. RESULTS

All results after adequate simulation in DigSILENT PowerFactory 15.1 is reported as seen in compliance with the IEEE standard. Results contained in this chapter comprises of Load flow before and after optimal placement of switchable shunt capacitors on appropriate bus bars.

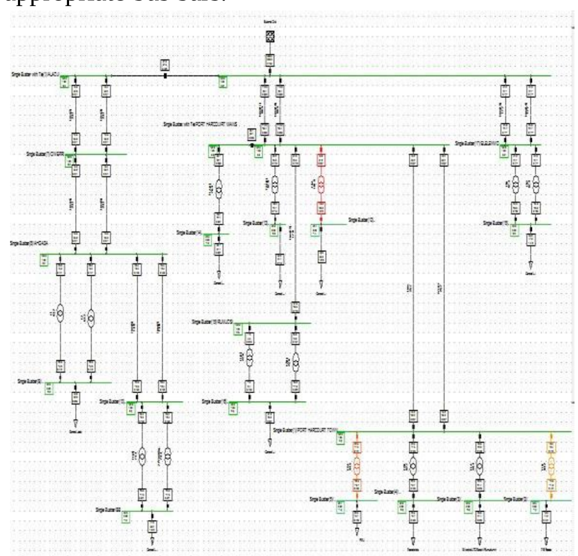

Figure 3 : Load Flow Result of Existing Network State

Figure 3 shows a diagnostic report of the 21 bus, 15 transformer and 11 load Port Harcourt sub-transmission and primary distribution network under consideration. The voltage level or profile at all buses were satisfactorily in compliance with the $\pm 5\%$ IEEE voltage drop regulation whereas issues of overloading were recorded in three (3) out of the fifteen (15) distribution transformers in the analyzed system.

From figure 3 the three affected distribution transformers are flagged red which is an indication of overload. Overloading of a distribution transformer according to the IEEE standard is loading above 80%. Summarily, all buses are green, all transmission lines are black and 12 out of 15 primary distribution transformers are black indicating good and satisfactory working condition.

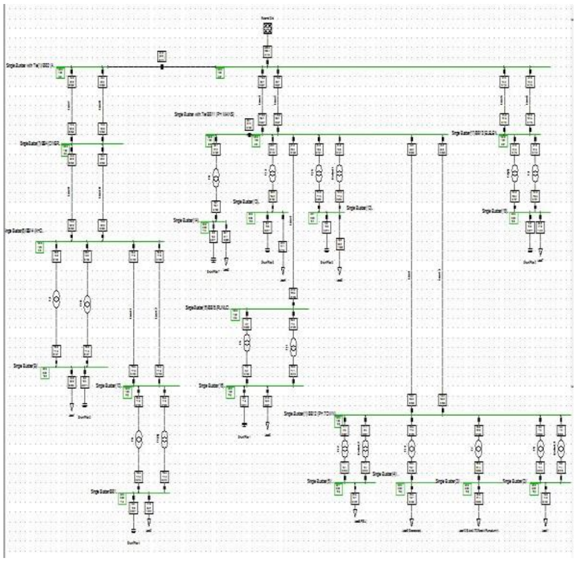

Figure 4: Load Flow Result for Modified Network State

Evidently, Figure 4 reveals a clear transformation of the network from the deficient existing state to an optimized modified state with the inclusion of three (3) relief transformers for overload remediation and 70 capacitor banks for reactive power compensation located at seven (7) load buses.

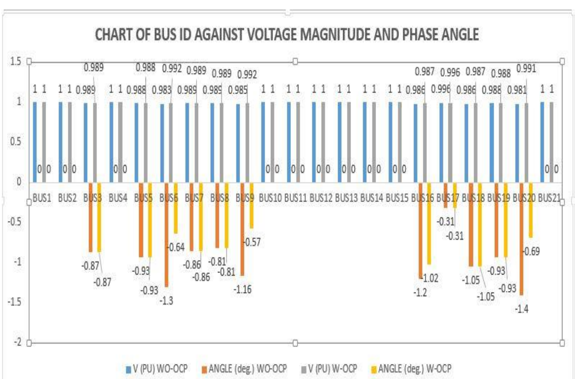

Figure 5: Result of Voltage Magnitude and Phase Angle with and without OCP

From the results in Figure 4 it is observed that five (5) out of twenty-one (21) buses have varying values between the pre-OCP and post-OCP results. The voltage magnitude and phase angular values in Buses 6, 9, 16, 18 and 20 were incremental and optimal with the introduction of adequate capacitors against the normal state of the network. All pre and post simulation values for voltage magnitude and phase angle in spite of the variations still fall within the IEEE $\pm 5\%$ voltage regulation.

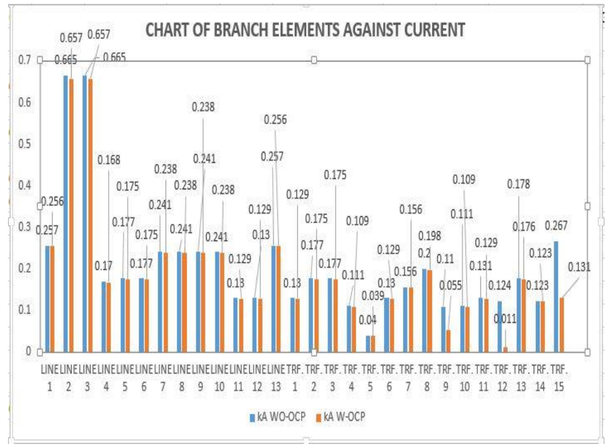

Figure 6: Result of Current Flow in Branch Elements with and without OCP

It is observed that in Figure 6 except for transformer 13 (TRF. 13) where current values for pre and post OCP are equal all other branch elements in the post OCP domain are having a current value slightly lower than the pre-OCP values. This a clear indication of reduced heating of conductor and losses.

From the above results, in order of significance, the least differential value between the pre and post OCP result is experienced in lines 1 and 13 whereas the highest differential value is experienced in transformer 13.

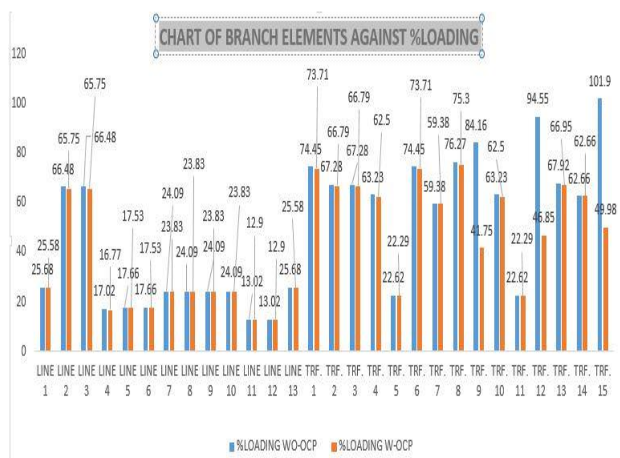

Figure 7: Result for Loading of Branch Elements with and without OCP

In figure 7 the loading of all branch elements (lines and transformers) were reduced in the presence of adequate capacitors in conformity with the IEEE less than 80% statutory loading value. The reduction as contained in figure 4.5 is not selective but all-inclusive due to its reflection on all branch elements. The highest reduction is experienced in transformer 15 while the least reduction is jointly experienced in line 1 and 13.

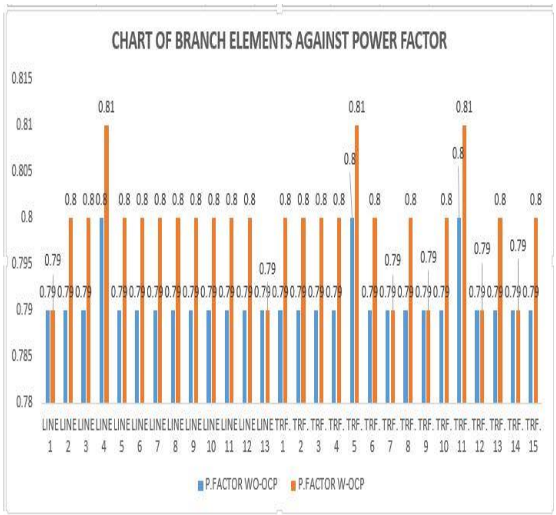

Figure 8: Result of Power Factor in Branch Elements with and without OCP

Comparative analysis on figure 8 shows that in exception of four elements (Line 1, Line 13, TRF.7 and 13) where power factor values are equal in magnitude all other elements are experiencing an incremental value of 0.01 in the presence of adequate capacitors. This increment justifies the need for and relevance of the capacitors introduced in the system.

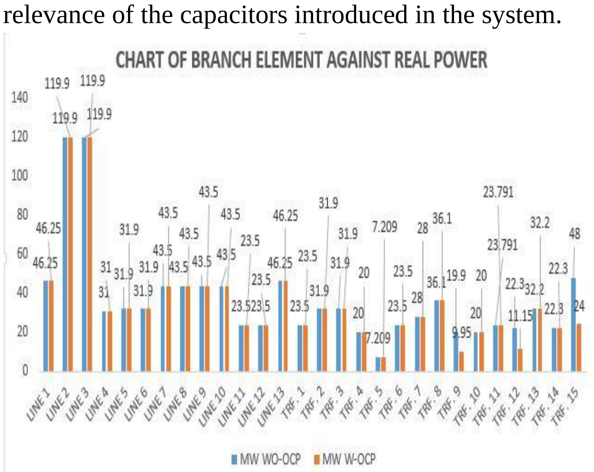

Figure 9: Result of Real Power Flow in Branch Elements with and without OCP

The result in figure 9 obviously show that the amount of power flow in all branch elements are invariable except for TRF. 9, 12 and 15 where the least and highest variation in power (MW) is recorded in TRF. 9 and 15 respectively.

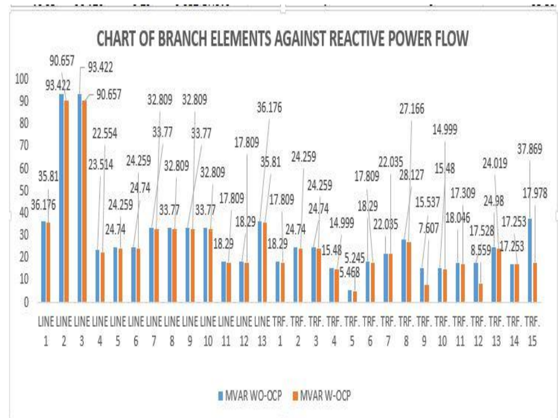

Figure 10: Result of Reactive Power Flow in Branch Elements

Reactive power flow in the system after introducing appropriate capacitor banks yielded a drastic decrease in value in all branch elements compared to the result of the existing (without OCP) state.

The highest reactive power flow reduction margin is recorded at TRF. 15 where the pre-OCP value of 37.896 $is\ reduced\ to$ 17.978 $MVAR$ after post-OCP simulation.

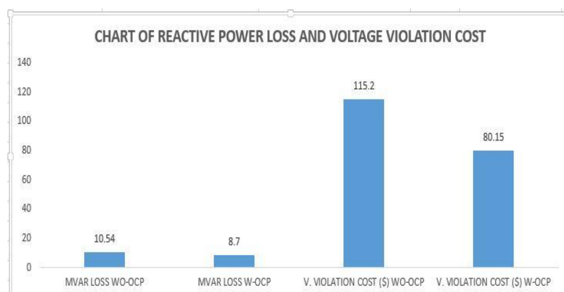

Figure 10: Results for MVAR Power Loss and Voltage Violation Cost with and without OCP

The effect of the variations in network parameters as a result of network modification through optimal capacitor placement (OCP) is further summarized in terms of losses and voltage violation cost. Figure 4.9 contains values for $\boldsymbol{MVAR}$ losses and voltage violation cost in dollar.

With the absence of real power loss in the pre and post OCP results, a loss and voltage violation cost value of

$10.54\ MVAR\ and$ \$115.2 are recorded after pre-OCP simulation whereas $8.7\ MVAR\ and$ \$80.15 were obtained as loss and voltage violation cost values after post-OCP simulation. The results contained in figure 4.9 translates into improved system efficiency and reliability with increased profit margin.

CONCLUSION

The AI-based optimization technique known as Tabu Search was proposed and implemented on the 21 bus 132/33kV sub-transmission and distribution network. The TS algorithm was able to improve the power system performance through optimal allotment of seventy (70) capacitor banks of $0.96\ MVAR$ across seven (7) load buses. The validity of the algorithm was proven through comparative analysis between the existing and modified network load flow performance.

Summarily the performance of the multi-objective Tabu search algorithm (TSA) for optimal capacitor placement (OCP) was viewed in the light of power loss and voltage violation cost. Upon successful implementation of the TSA to the power network under investigation, a total of 67.20MVAR was injected into the system resulting to optimization of voltage profile and minimization of reactive power loss to the tune of 17.5%.

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