# Impact of Shunt Capacitor Penetration Level in Radial Distribution System Considering Techno-Economic Benefits

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***ABSTRACT:*** Shunt Capacitor (SC) integration in radial distribution networks is a method utilized to minimize power losses and huge voltage drops. In other to obtain these maximum benefits, they should be optimally allocated. To this effect, researchers have used various optimization methods for solving SC allocation problems but most have not considered how the penetration level of SC into the radial distribution system affects these benefits. The goal of the paper, therefore, is to determine the most sensitive buses to reactive compensation and investigate the effect of the penetration level of SC on the techno-economic benefits. Load flow was performed for the base case to determine the steady-state performance of the system and the most sensitive buses were selected using New Voltage Stability Index (NVSI) technique. The size of the SC was increased in step of these buses, in turn, to determine SC penetration level impact on the techno-economic benefits. The approach was implemented on IEEE 33-bus and practical Nigerian radial distribution networks. The results showed that appropriate penetration of SC on networks leads to reduction of power losses, voltage profile improvement as well cost reduction resulting in high net savings.

***KEYWORDS:*** Shunt capacitor, Radial distribution system, Penetration level, Power losses, Voltage stability index.

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## I. INTRODUCTION

The radial distribution system is becoming a large and complex network resulting in increase in the network overall power loss and voltage magnitude violations. Studies show that about 13% of the overall generated power constitutes $I^2R$ losses at the distribution level (Rao et al., 2011). Several methods have been reported in works of literature for loss minimization and voltage profile enhancement of the distribution network. One of the popular techniques is capacitor placements. Shunt capacitor (SC) is majorly utilized to reduce distribution system power loss, improve bus voltage magnitudes and voltage stability index, power factor correction, power quality improvement, minimization of the total harmonic distortion (THD), increase system capacity and overall system performance (Elsheikh et al., 2014; Masoum et al., 2004).

Nevertheless, compensation benefits are functions of the location and size of SC. Generally, SC allocation's main objective is to determine the integrated SC optimal placement and size by minimizing cost using loss minimization through proper SC placement while reducing the costs of the shunt capacitor (Golam-Mostafa et al., 2020). Studies indicate that inappropriate placement of SC on radial distribution networks usually leads to an increase in power losses, poor voltage profile, and low net cost savings due to power losses (Ayanlade and Komolafe, 2019). In other words, reactive power over injection into the network will negatively affect the efficiencies and performances of radial distribution systems.

Many optimization solution methodologies and models exist in literature to optimally allocate SCs in distribution networks. The approaches earlier proposed, which are otherwise referred to as analytical numeric programming like local variation method (Ponnavaiko and Rao, 1983) and mixed-integer programming techniques (Baran and Wu, 1985; Khodr et al., 2008) were used for solving the problem. Recently, different meta-heuristic techniques were proposed for SC placement considering various techno-economic objectives such as power loss reduction, reduction of overall cost, improvement of net savings, and bus voltages.

Various optimization algorithms such as Genetic Algorithm (GA) (Pazouki et al., 2015), Fuzzy (Bhattacharya and Goswami, 2008), Fuzzy-GA (Gampa and Das, 2016), Particle Swarm Optimization (PSO) (Kanwar et al., 2015), Immune Algorithm (IA) (Huang, 2000), Plant Growth Simulation Algorithm (PGSA) (Huang and Liu, 2012), Tabu Search (TS) (Pires et al., 2005), Memetic-Algorithm Approach (Mendes et al., 2005), TLBO algorithm (Sultana and Roy, 2014), Ant Colony (Kaur and Sharma, 2013), Graph Search Algorithm (GSA) (Shuaib et al., 2015), Artificial Bee Colony (ABC) (Abu-Mouti, and El-Hawary, 2011), Whale Optimization Algorithm (WOA) (Prakash, and Lakshminarayana, 2017), Flower Pollination Algorithm (Tamilselvan et al., 2018), Cuckoo Search Algorithm (CSA), (Uchendu, 2020; Salimon et al., 2020), Algorithm (FA)

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(Reddy and Suresh, 2014), Hybrid Algorithm (Goswami et al., 1999) and Polar Bear Optimization Algorithm (Saddique et al., 2020) have been used for optimal sizing and location of shunt capacitor considering various objectives as techno-economic benefits.

Most of the aforementioned literatures have determined the optimal size and location of Shunt Capacitor (SC) that will result in maximum power loss reduction and other techno-economic benefits being considered using various optimization algorithms. However, there is need to investigate how gradual increase in the size of the SC in relation to the total reactive power demand affects these benefits. In this paper, the penetration level of the SC into the distribution system is gradually increased from 0% to 100% of the total reactive power demand of the network in step of 10. This will vividly illustrate analytically how the penetration level of SC affects the techno-economic benefit derivable from the integration of SC into the radial distribution system and point of maximum benefit can be easily deduced from the illustration.

This paper, therefore, seeks to select the most sensitive buses among the numerous buses of the distribution system for SC integration and investigates how the penetration level of SC affects techno-economic benefits including active and reactive power losses together with voltage profile and net cost savings due to power losses. This paper has the advantage of determining the accurate capacity of SC penetration which gives the optimal value of any of the benefits.

## II. METHODOLOGY

### A. Load Flow for Distribution System using BIBC-BCBV Technique

Radial distribution systems are ill-conditioned networks characterized by high resistance to reactance ratio, untransposed lines, and so on. Consequently, the conventional load flow techniques may not be accurate. Therefore, Node Injection Branch Current - Bus Voltage Branch Current (BIBC-BVBC) power flow technique proposed in (Salimon et al. 2019) was used for solving the power flow problems in this research.

The most unstable and sensitive buses to reactive compensation are selected for penetration of SC using a New Voltage Stability Index (NVSI) presented by Gupta and Kumar (2018).

$$NVSI = \frac{4R_{ef}}{V_e^2}\left(\frac{Q_f^2}{P_f} + P_f\right) \tag{1}$$

NVSI magnitude computed for each of the buses determines the vulnerability of the bus to voltage collapse. Under normal circumstances, NVSI magnitude is expected to tend to zero for stability and one for instability. The bus which exhibits the maximum value of NVSI is considered as the most sensitive bus and consequently optimal placement of SC.

### B. Connection of Shunt Capacitor to the Distribution System

The SCs were modeled as negative loads and placed on the network buses. If $Q_{li}$ denotes the reactive power absorbed at bus *i*, on connecting SC, the new reactive power at bus *i* can be written as in Eq. (2).

$$Q_{nli} = Q_{li} - Q_{SC} \tag{2}$$

where,

$Q_{nli}$ = new reactive power absorbed.

## III. TECHNO-ECONOMIC IMPACT OF SHUNT CAPACITOR ON THE NETWORK

The SC impact on the network were analysed considering the active and reactive power losses as a result of its placement on the distribution network and the effect of its placement on the total cost and the voltage profile. A MATLAB script code was developed to obtain the load flow solution before and after integration of SC. The active and reactive power losses together with the total cost and voltage profile are also obtained with the developed script code.

### A. Loss Determination in the Distribution System

The current through a line *i*, between buses *e* and *f*, is denoted as $I_i$, the active and reactive power losses are determined using (3) and (4).

$$P_{loss} = I_i^2 R_{ef} \tag{3}$$

$$Q_{loss} = I_i^2 X_{ef} \tag{4}$$

where,

$R_{ef}$ = line resistance,

$X_{ef}$ = line reactance.

$I_i$ is computed from the load flow analysis using BIBC-BCBV technique. The overall active and reactive power losses can computed using Eqs. (5) and (6).

$$TP_{loss} = \sum_{i=1}^{N} P_{loss} \tag{5}$$

$$TQ_{loss} = \sum_{i=1}^{N} Q_{loss} \tag{6}$$

where,

N = total number of line

### B. Determination of Voltage Profile Index (VPI)

For the purpose of comparison of the voltage profile of various scenario, an index was used to denote the extent to which the voltage matches the nominal value (Ayodele et al., 2015). VPI can be expressed mathematically as in Eq. (7).

$$VPI = \log_{10}\left(k\alpha\left|\frac{1}{V_\mu - 1}\right|\right) \tag{7}$$

$V_\mu$ and $k$ can be determined as follows:

$$V_\mu = \frac{1}{N}\sum_{i=1}^{N} V_i \tag{8}$$

$$k = 1 - V_\sigma \tag{9}$$

$$V_\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(V_i - V_\mu\right)^2} \tag{10}$$

where,

$N$ = no of buses

$V_i$ = voltage magnitude at bus $i$

$V_\mu$ = mean bus voltage

$V_\sigma$ = bus voltage standard deviation

For scenarios A and B, if $VPI_A > VPI_B$, scenario A gives a better voltage profile.

### C. Determination of Economic Benefit for Shunt Capacitor Penetration

The economic factor is the overall annual cost due to network power loss and reactive power compensation. The reactive power compensation cost comprises installation purchase, and operation cost of capacitors.

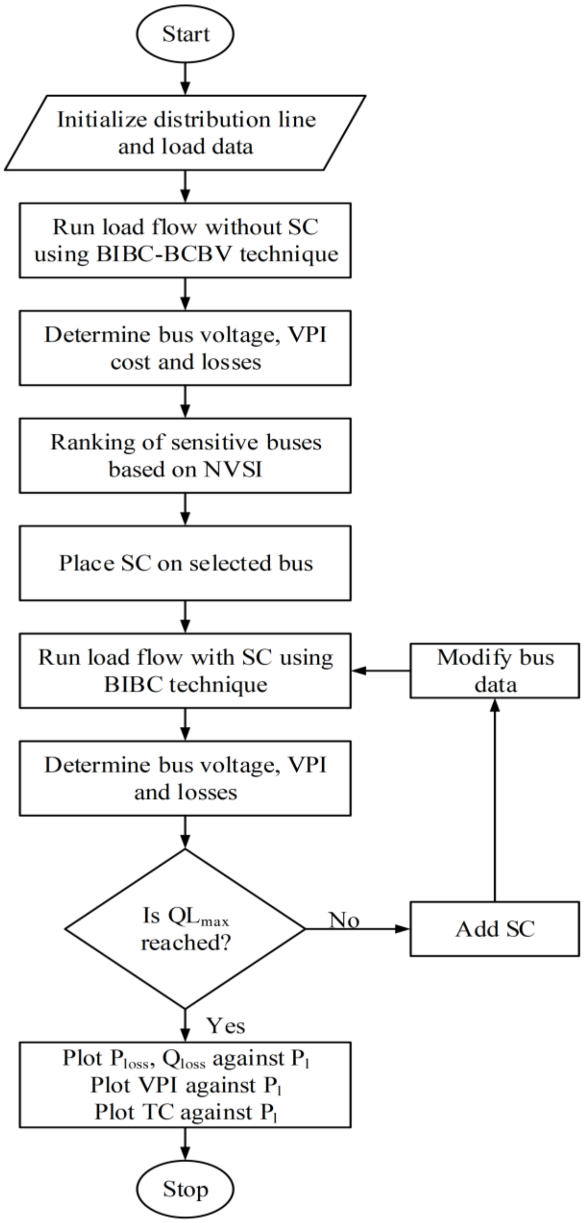

**Figure 1: Flowchart to obtain the impact of SC penetration.**

Total cost = power loss cost + reactive power compensation cost

$$TC = k_p \times P_{loss} + \alpha\left[\left(C_{inst} \times N\right) + C_{cap}\sum_{i=1}^{N} Q_{ci}\right] + \left(C_{ope} \times N\right) \quad (11)$$

where,

$P_{loss}$ = total power loss after SC integration

$K_p$ = annual cost per unit of power losses ($/kW)

$C_{inst}$ = capacitor purchase cost

$Q_{on}$ = shunt capacitor capacity

$C_{ope}$ = capacitor operating cost

$\alpha$ = depreciation factor

$N$ = number of shunt capacitor

Therefore, the net cost saving due to compensation is given:

$$NCS = TC - (K_p \times P_{loss_0}) \quad (12)$$

Where, $P_{loss\_0}$= total power loss before SC integration

D. Penetration Level

Penetration level (PL) can be defined as the magnitude of reactive power demand that is met by SC. It is mathematically expressed as in (13).

$$Q_L = \frac{Q_{SC}}{Q_{load}} \times 100\% \quad (13)$$

A 0% $Q_L$ means that the reactive power demand is completely supplied by the network and a 100% $Q_L$ means that the reactive power demand is met by SC only.

## IV. RESULTS AND DISCUSSION

Simulations were performed to investigate the effect of SCs penetration level on losses, voltage profile, and net cost savings on the distribution systems. Matlab script codes were developed to solve the power flow network problems without and with shunt capacitor integration using Matlab R2020a on a core i3 computer clocked at 2.20 GHz. The methodology was evaluated on IEEE 33-bus and Nigerian Ayepe 34-bus networks obtained from Adepoju *et al*. (2019) and Salimon *et al*., (2020), respectively. The cost specifications for the shunt capacitor are shown in Table 1. Two scenarios were created to clearly show the possible impacts of the SC on the distribution system. The first scenario represents the Base Case (BC), a condition in which no SC was placed on the network. The other scenario denotes the situation in which the SC is connected to the distribution system at different buses chosen from the first five rankings of the NVSI values obtained from the base case and then increasing the penetration level.

**Table 1. Cost specification for the shunt capacitor (Goswami et al., 1999)**

| Parameter | Description | Value |
|---|---|---|
| $K_p$ | Annual cost per unit of power losses ($/kW) | 525.6 |
| $C_{inst}$ | Installation cost ($/location) | 1600 |
| $C_{cap}$ | The purchase cost of the capacitor ($/kVAr) | 25 |
| $C_{ope}$ | Operating cost of the capacitor ($/year per location) | 300 |
| $\alpha$ | Depreciation factor | 0.1 |

### A. Standard IEEE 33-Bus Network

The scenario of the BC allows comparison with when SC is placed. The simulation was carried out for BC. The overall active and reactive power demands, active and reactive power losses, and VPI are given in Table 2. The NVSI values are illustrated in Figure 2. The table shows that the active and reactive power losses are 211 kW and 143 kVar, respectively, while the VPI and total cost due to power losses are 1.25 and $ 110, 896. From Figure 2, the first five buses with the highest ranking are buses 30, 8, 25, 24, and 31 with corresponding NVSI values of 0.02981, 0.01228, 0.01226, 0.01221, and 0.005276, respectively. These are the first five buses sensitive to capacitive compensation according to the NVSI formula utilized in the methodology. Hence, they are selected for connection and penetration of the shunt capacitor.

**Table 2. Result for base case scenario for standard IEEE 33-bus system.**

| Parameter | Value |
|---|---|
| Total load active power demand in kW | 3715 |
| Total load reactive power demand in kVar | 2300 |
| Total active power loss in kW | 211.00 |
| Total reactive power loss in kVar | 143.00 |
| Voltage profile index (VPI) | 1.25 |
| Total cost in $ | 110, 896 |

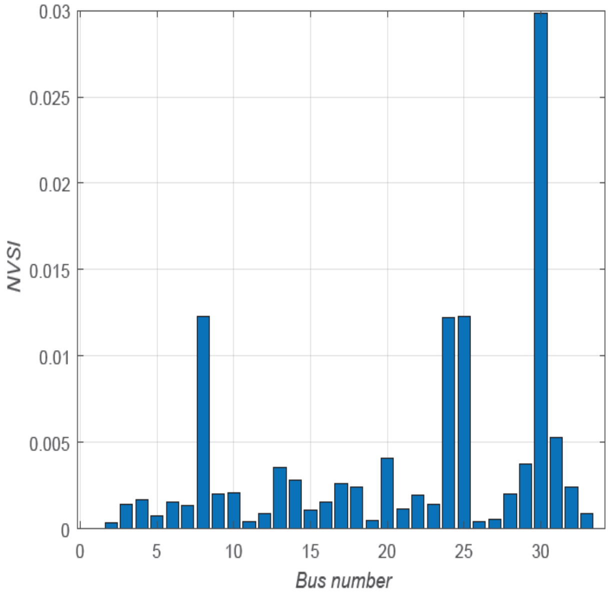

**Figure 2: NVSI values for IEEE 33-bus network.**

The SC was placed at different sensitive chosen buses in turn. The result for the active power and reactive power losses, together with VPI and net cost savings when SC was placed at the sensitive buses when the penetration level was continuously increased, are illustrated in Figures 3-6, respectively.

From Figures 3 and 4 it was noted that the active and reactive power losses exhibit a bath-tub behaviour as SC penetration level increases. This shows that at the initial penetration (when SC was low), the contribution of SC to the network in minimizing the total real and reactive power losses is positive. Nevertheless, as the penetration level increased beyond a point, the active and reactive power losses started increasing, which implies that, at higher SC penetration beyond a minimum point, the active and reactive power losses increase. It could also be noted from the figures that a penetration level ($PL_{min}$) exists where the active and reactive power losses are the least. This point, nevertheless, changes from one bus to another. These points occur at 55%, 45%, 45%, 40%, and 30% penetration levels for buses 30, 31, 8, 24, and 25, respectively for both active and reactive power losses. The corresponding real power losses in kW and reactive power losses in kVar at this point are 151.4, 158.0, 172.2, 198.5, 200.8; and 103.9, 109.3, 118.9, 136.8, and 137.9, respectively. These reveal that minimum real power losses occur between 30 to 55% penetration level for the most sensitive buses which indicate that the total active and reactive power loss reduction continually improved until about 30-55% penetration. It was also noted that the losses (active and reactive power) are the least at bus 30.

The VPI as illustrated in Figure 4 reveals a direct proportion between the VPI and penetration level as there is continual voltage profile improvement with the penetration of SC in comparison with the base case scenario. This is because the SC injects reactive power into the network to enhance the voltage profile.

The net cost saving due to capacitive compensation against the penetration level is illustrated in Figure 6. It is clear from the figure that the net savings increases at low SC penetration (initial penetration) until a maximum point (PLmax). This is the point at which the net saving due to SC penetration is maximum. Beyond this point ($PL_{max}$), the net saving began to decrease with increasing penetration of SC. This PLmax varies from bus to bus. These points occur at 50%, 45%, 45%, 40% and 25% penetration level for buses 30, 31, 8, 24 and 25, respectively. The corresponding net savings in $ at this point are 27 900, 24 935, 17 270, 3 887, and 3 609, respectively. This infers that the maximum net savings occur between 25- 50% penetration level for the chosen sensitive buses which indicates that the net savings were continually increased until about 25-50% penetration. It was also observed that the net saving due to capacitive compensation is highest at bus 30.

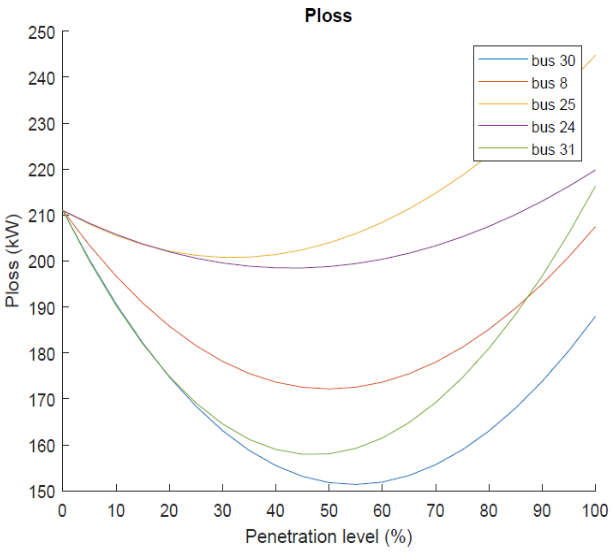

**Figure 3: Total active power loss against the penetration level of SC.**

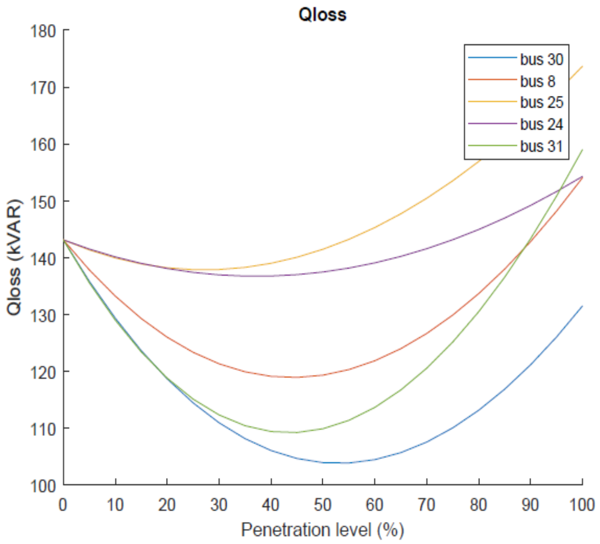

**Figure 4: Total reactive power loss against the penetration level of SC.**

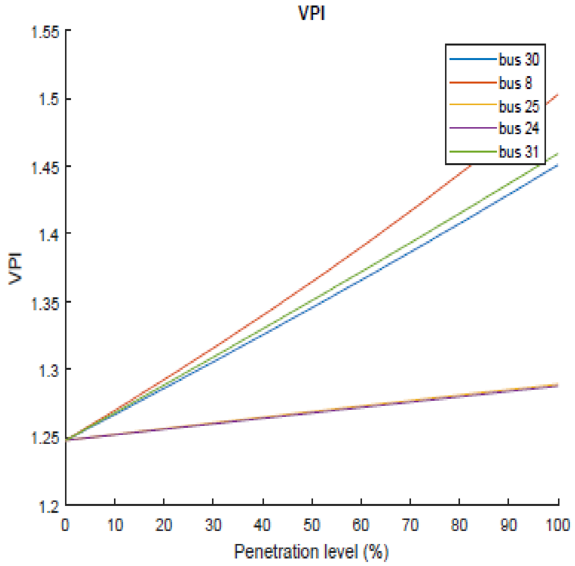

**Figure 5: Voltage profile index against the penetration level of SC.**

The optimal size of SC for minimum power loss and maximum net savings can be deduced from the most sensitive bus with the least loss and maximum savings from Figures 3 and 6, respectively. This can be used as a benchmark for confirmation of the results of optimal values of optimal allocation of SC problems using any optimization methods in a distribution system. For instance, $PL_{min}$ of Figure 3 is least in bus 30 and this can be taken as the optimal bus. The value of $PL_{min}$ is 55% which corresponds to 1 265 kVar (obtained from $PL$ multiplied by the network total reactive power demand). The total active and reactive powers at this point are 151.4 kW and 103.9 kVar, respectively. These are compared with the solutions of some recent optimization techniques in SC/D-STATCOM allocation problems in Table 3.

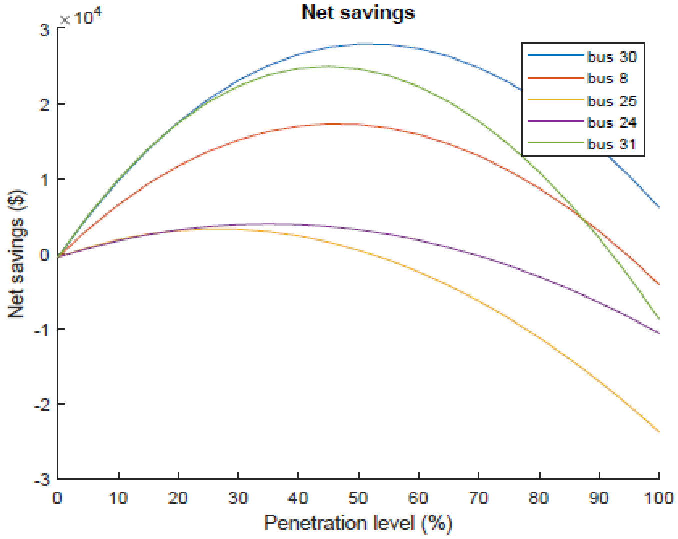

**Figure 6: Net cost-saving against the penetration level of shunt capacitor.**

## *B. Nigerian Ayepe 34-Bus System*

The scenario of the BC allows comparison with when SC was placed. The simulation was carried out for BC and the overall active and reactive power demands, active and reactive power losses, and VPI are given in Table 4. The NVSI for Ayepe 34-bus network is illustrated in Figure 7. The first five buses with the highest ranking are buses 15, 24, 9, 5, and 2 with corresponding NVSI values of 0.00651, 0.00345, 0.00328, 0.00295, and 0.00257, respectively. These are the first five buses sensitive for capacitive compensation according to the NVSI formula utilized in the methodology. Hence, they are selected for connection and penetration of SC in the Ayepe 34-bus system.

The SC was placed at different sensitive chosen buses in turn. The result for the active and reactive power losses, VPI, and net cost savings when SC was placed at the selected buses with an increase in penetration level is illustrated by Figures 8-11, respectively.

Figures 8 and 9 showed that the active and reactive power losses exhibit a bath-tub characteristic with increasing SC penetration level. This indicates that at the initial penetration (when SC was low), the contribution of SC to the distribution system in minimizing the overall active and reactive power losses is positive. Nevertheless, as the penetration level is increased beyond a point, both the active and reactive power start increasing, implying that, at SC higher penetration level beyond a minimum point, the active and reactive power losses increase. Also, from the figures, there exists a penetration level ($PL_{min}$) at which the active and reactive losses are the least. This point, however, changes from one bus to another. These points occur at 75%, 65%, 95%, 100%, and 100% penetration levels for buses 15, 24, 9, 5, and 2, respectively for both active and reactive power losses. The corresponding active power losses in kW and reactive power losses in kVar at this point are 611.2, 620.2, 620.9, 679.2, and 743.7; and 11.73, 119, 130.36, 130.3, and 142.7, respectively.

**Table 3. Comparison of results for IEEE 33-bus**

| Methods | Year | Description | SC/DSTATCOM (Location) | P-loss (KW) | Q-loss (kVAr) | % Ploss | % Qloss |
|---|---|---|---|---|---|---|---|
| ---- | ---- | Base case | ---- | 211.0 | 143.1 | ---- | ---- |
| Analytical (Gopiya *et al.*) | 2013 | 1SC | 1000(33) | 164.6 | N.A. | 22.83 | ---- |
| IA (Taher and Afsari) | 2014 | 1DSTATCOM | 962.49(12) | 171.8 | N.A. | 18.57 | ---- |
| IP (Shuiab *et al.*) | 2015 | 3SCs | 450(19),800 (29), 900(30) | 171.8 | N.A. | 18.21 | ---- |
| SA (Shuiab *et al.*) | 2015 | 3SCs | 450(10),900(14), 1000(33) | 151.8 | N.A. | 27.74 | ---- |
| CSO (Yuvaraj *et al.*) | 2017 | 1DSTATCOM | 1370.50(23) | 175.0 | N.A. | 17.05 | ---- |
| MVO (Hassan and Zellagui) | 2019 | 1DSTATCOM | 1286.50(30) | 151.4 | 104.0 | 28.25 | 27.36 |
| CSA (Salimon *et al.*) | 2020 | 1SC | 1200 (30) | 151.5 | 103.4 | 28.18 | 27.78 |
| Proposed method | 2021 | SC penetration | 1265 (30) | 151.4 | 103.3 | 28.25 | 27.79 |

**Table 4: Result for base case scenario for Ayepe 34-bus system.**

| Parameter | Value |
|---|---|
| Total load active power demand in kW | 4 120 |
| Total load reactive power demand in kVar | 2 050 |
| Total active power loss in kW | 762.64 |
| Total reactive power loss in kVar | 146.37 |
| Voltage profile index (VPI) | 0.8430 |
| Total cost in $ | 400,840.00 |

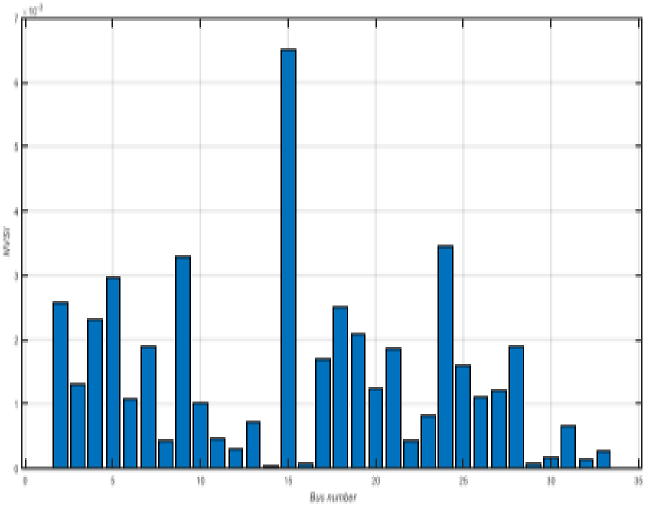

**Figure 7: NVSI values for Ayepe 34-Bus System.**

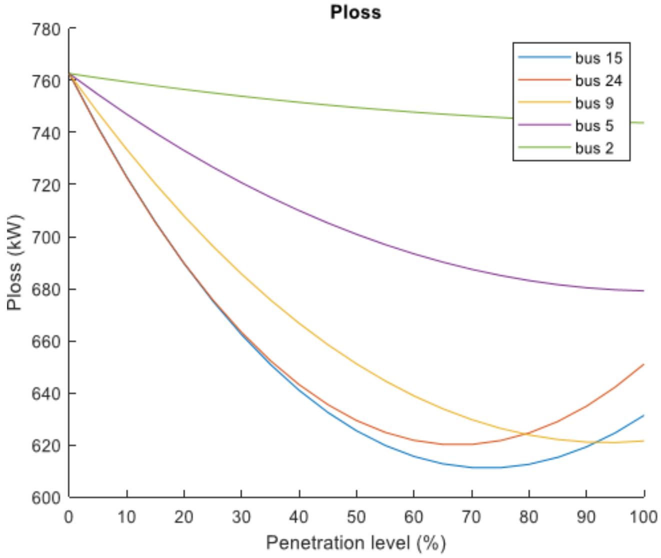

**Figure 8: Total active power loss against the penetration level of SC.**

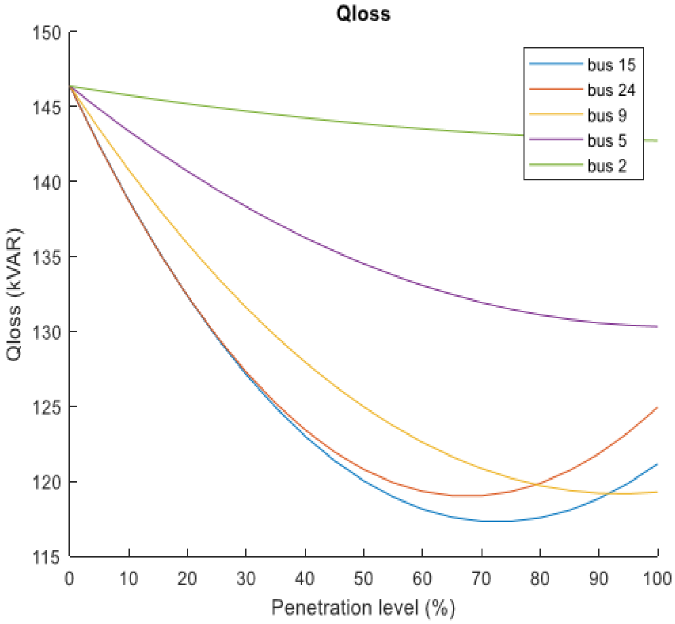

**Figure 9: Total reactive power loss against the penetration level of SC.**

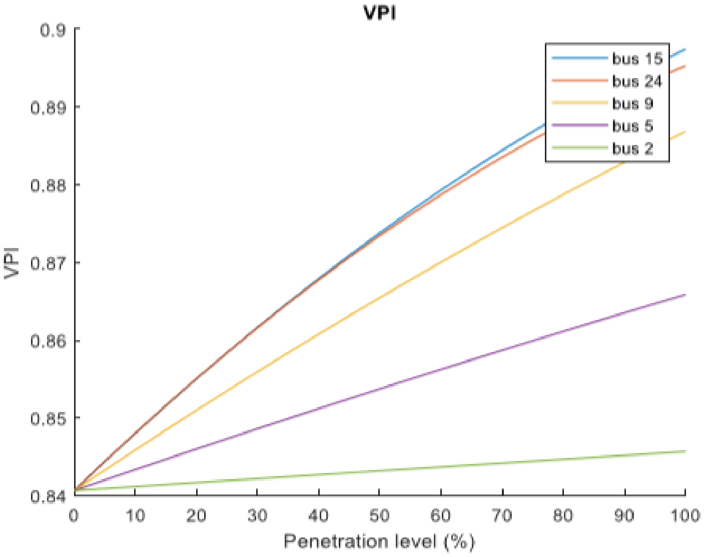

**Figure 10: Voltage profile index against the penetration level of SC.**

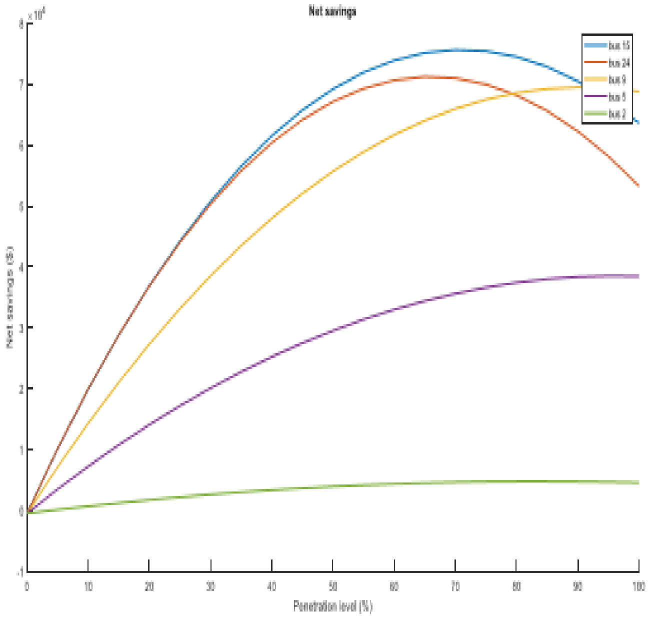

**Figure 11: Net cost saving against the penetration level of shunt capacitor.**

These reveal that minimum active power losses occur between 50 to 75% penetration level for the most sensitive buses which imply that the overall active and reactive power loss reduction improved continually until about 50-75% penetration. It was also noted that the loss is minimum at bus 15.

The VPI as illustrated in Figure 10 reveals a direct proportion between the VPI and penetration as there was continual voltage profile improvement with SC penetration in comparison with BC scenario. This is because SC injects reactive power to the network for voltage profile improvement.

The net cost saving due to capacitive compensation against the penetration level is illustrated in Figure 11. It is crystal clear from the figure that the net savings increases at low SC penetration (initial penetration) until a maximum point ($PL_{max}$). Beyond this point ($PL_{max}$), the net saving began to decrease with increasing penetration of SC. This $PL_{max}$ varies from bus to bus. These points occur at 75%, 65%, 95%, 100% and 100% penetration level for buses 15, 24, 9, 5 and 2, respectively. The corresponding net savings in $ at this point are 75 430, 71 210, 69 360, 38 490, and 4 573, respectively. This infers that the maximum net savings occur between 35 - 70% penetration levels for the chosen sensitive buses meaning that the net savings were continually increased until about 35-75% penetration. It was also observed that the net saving due to capacitive compensation is highest at bus 15.

The optimal size of SC for minimum power loss and maximum net savings can be deduced from the most sensitive bus with the least active and reactive power losses and maximum savings from Figures 8, 9, and 11, respectively. This can be used as a benchmark for confirmation of the results of optimal values of optimal allocation of SC problems using any optimization techniques in a distribution network. This is dependent on the condition that the index selects the buses that truly indicate the most sensitive buses. For instance, the $PL_{min}$ of Figure 8 is least in bus 15 and this can be taken as the optimal bus. The value of $PL_{min}$ is 75% which corresponds to 1 538 kVar (obtained from $PL$ multiplied by the overall reactive power demand). The overall active and reactive powers at this point are 611.2 kW and 11.43 kVar, respectively.

## V. CONCLUSION

The SC penetration effect on active and reactive power losses, together with the voltage profile of the networks were investigated. From the results, the following can be concluded:

i) The capacitive compensation reduces the power losses and costs due to power losses occurring in a distribution system. However, the loss and cost recorded vary among the sensitive buses that were investigated in the study.
ii) The SC impacts on power losses formed a bath-tub characteristic curve with an increase in penetration level which implies that at a low penetration level, the losses are minimized. However, as SC penetration level is increased, the power losses start increasing. This indicates that there is a maximum penetration level beyond which SC increases the system power losses.
iii) The impacts of the SC on the net savings formed a shape that shows that at a lower penetration level, the net savings are increased, however, as penetration is increased, a point will be reached beyond which the net savings start decreasing. This implies that maximum penetration level exists beyond which the net savings start increasing with SC penetration level.
iv) The voltage profile is directly proportional to SC penetration level.

Future work can consider the impact of the penetration level of multiple shunt capacitors on the buses of the distribution system.

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