Applications of DG and Shunt Capacitor in Hill Top Network Enugu, Nigeria for Stability Improvement and Loss Minimization

KINGSLEY U. OKEKE[1], EMMANUEL A. ANAZIA[2], JUDE I. ANEKE[3], CHIDIEBERE A. OKEKE[4], AUGUSTINE O. ANIAGBOSO[5]

[1, 2, 3, 5] Department of Electrical Engineering, Nnamdi Azikiwe University, Awka, Nigeria,

[4] Universiti Putra Malaysia (UPM)

Abstract- The incorporation of Distributed Generation (DG) and shunt capacitor in a distribution system simultaneously for voltage profile improvement and minimization power losses were addressed in this paper. For this purpose, the Voltage Stability Index (VSI) Method and Power Loss Index (PLI) approach were utilized to determine the suitable position of DGs and shunt capacitors. In addition to that, technical and economic analyses were examined for various combinations of DGs and shunt capacitors. The proposed methodology was successfully demonstrated on 38-bus Hilltop 11kV radial networks with four different load scenarios on MATLAB/PSAT environment. The effect of the installation of the distributed Generation (DG) and shunt capacitor in a distribution system was studied and analyzed and the result was compared with the network, without the installation of neither distributed generators nor shunt capacitor banks. To achieve this aim, a load flow method using Newton-Raphson technique was used to estimate unknown variables in the network such as voltage, angle, MVAR and MW, before the installation of the DGs and shunt capacitor banks. It was observed that the majority of the buses were below the standard operating voltage range, (0.95pu –1.05pu).From the outcomes, it was noted that the real and reactive energy loss reduction calculated in case-4 (simultaneous installation of both DG units and capacitor banks) was 37.10% and 49.95% respectively which is better as compared to the other two cases which recorded 27.75% real power reduction and 33.28% reactive power reduction for case 2 (installation of only DG units) and 25.91% real power reduction and 32.28% reactive power reduction for case 3 (installation of only capacitor banks). The proposed methodology also demonstrated the capability for solving the problem of voltage deviation and improvement in voltage profile. Case-4 (simultaneous installation of both DG units and capacitor banks) showed better results than the other two cases. From the outcomes, it is noted that the voltage profile improvement calculated in case-4 was 6.09% which is better as compared to the other two cases which recorded 5.12% improvement for case 2 (installation of only DG units) and 5.70% improvement for case 3 (installation of only capacitor banks). Hence, in the four scenarios, case-4 (simultaneous installation of both DG units and capacitor banks) showed better results than the other three cases.

Indexed Terms- Distributed Generator, Power Loss, Voltage Profile, Shunt Capacitor

I. INTRODUCTION

There has been incessant daily increase in load demand, this increase in demand causes increased stress in the interconnected network. The transmission and distribution networks are being over loaded and experience great loss. The poor availability of power supply, frequent power cuts and indiscriminate power outages pose a great threat to the technological and economic advancement of the country (Sujiang, 2018). In electrical power system, distribution system is a more complex network and having a higher power loss as compared to transmission network due to high R/X ratio. Reduction of such powerloss is a major challenge in front of distribution companies. The major outlooks for power loss reduction are Distributed Generation (DG) placement, capacitor placement and system re-configuration (Pradeepa, Ananthapadmanabha, Sandhya and Bandhavya, 2015).

In the last few years, DG placement has become a very renowned research area. After incorporating DG into a system, it provides several potential benefits such as voltage level enhancement, reduction of power loss and improve system stability (Mukul, Prasanta and Hitesh, 2017). Combination of both DG and shunt capacitor can play important role for reducing power loss and enhance voltage level to a great extent, if these are properly located with optimum size.

Historically, central plants have been an integral part of the electric grid, in which large generating facilities are specifically located either close to resources or otherwise located far from populated load centers. These, in turn, supply the traditional transmission and distribution T&D grid that distributes bulk power to load centers and from there to consumers. These were developed when the costs of transporting fuel and integrating generating technologies into populated areas far exceeded the cost of developing T&D facilities and tariffs. Central plants are usually designed to take advantage of available economies of scale in a site-specific manner, and are built as "one-off," custom projects.

These economies of scale began to fail in the late 1960s and, by the start of the 21st century, Central Plants could arguably no longer deliver competitively cheap and reliable electricity to more remote customers through the grid, because the plants had come to cost less than the grid and had become so reliable that nearly all power failures originated in the grid. Thus, the grid had become the main driver of remote customers' power costs and power quality problems, which became more acute as digital equipment required extremely reliable electricity (Takahashi, et al, 2005). Efficiency gains no longer come from increasing generating capacity, but from smaller units located closer to sites of demand (Lovins, 2007).

Distributed Generators (DG or embedded generators) are small generators (less than 10MW) that are connected to the distribution network of the power system. Their advantages are the ability to reduce or postpone the need for investment in the transmission and distribution infrastructure when optimally located; the ability to reduce technical losses within the transmission and distribution networks as well as general improvement in power quality and system reliability (Ogunjuyigbe, 2016).

The impact of distributed generator (DG) on the electricity industry is always determined in planning by carrying out load flow computations, especially when the penetration ratios are still relatively small. However, as the installed capacity of DG increases, its impact on the power system behavior becomes more expressed and will eventually require full-scale detailed dynamic analysis and simulations to ensure a proper and reliable operation of the power system with large amounts of DG (Ahmed Mohamed Azmy, 2005). Power flow provides a systematic mathematical approach to various bus voltage, their phase angles, active and reactive power through different branches, generators and loads under steady state condition. It is an important tool involving numerical analysis applied to power system (Murty, 2017).

The aim of this work, therefore, is to implement voltage security improvement of radial distribution network with distributed generation and shunt capacitor.The Hilltop 11kV distribution network has been adopted as the case test network for the radial distribution feeder. One of the main tasks for power engineers and researchers is to generate electricity from renewable energy sources (DGs), improving the voltage stability and availability of the grid to mitigate these lapses and at the same time reducing environmental impact of power generation.

1.2 The Case Study Networks

Modelling of the Hilltop 11kV Distribution Network, Enugu, Nigeria

This is a radial distribution network that receives supply from the Kingsway 33kV Injection Substation and supplies/feeds thirty-six (36) 11/0.415kV distribution substations (DSS). The popular DSS includes Radio Nigeria Tx Ngwo, Esbs Tx Station Ngwo, Colliery Hospital Iva Valley, Proda, Police Ngwo, Onu-Agu Ngwo, Mission/Step Ngwo, Ekeani Ngwo, Unity House Ngwo, Colliery Sec. Sch. Ngwo, Multichoice Esbs Tx Ngwo, Nursing Home Udi Siding, Colliery Hospital Iva Valley, Copex Iva Valley and many others. The feeder route length is about

22.385km long with 533 High-Tension electric poles. The network as extracted from EEDC Enugu metropolis distribution map (EEDC GIS Unit) is as sown on the MATLAB/PSAT model of the network (Figure 1). Figure 2 shows the expanded Sub-Block (Approved School) in Figure 1.

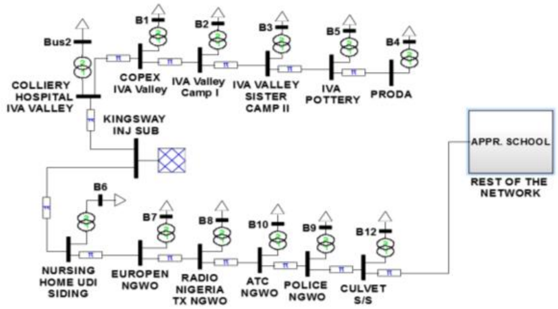


Figure 1: PSAT model of the Hilltop 11kV distribution network without DG units and Capacitor banks.

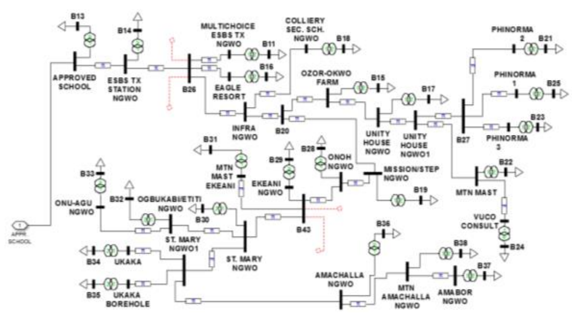


Figure 2: Expanded Sub-Block (Approved School) in Figure 1.

II. VOLTAGE STABILITY INDEX (VSI)

VSI is utilized to compute security level of a distribution network. Those buses which are having lowest index that will be the most critical buses and having more chances to voltage collapse. Hence, this approach is beneficial for determining weakest buses to provide real and reactive power compensation support to a network. It can be defined using (1) (Oladepo and Hasimah, 2019).

$$VSI_{(i+1)} = |V_i|^4 - 4\{P_{Li+1}R_{Li+1} - Q_{Li+1}X_{Li+1}\}^2 - 4\{P_{Li+1}R_{Li+1} + Q_{Li+1}X_{Li+1}\}|V_i|^2 \quad (1)$$

Following the VSI computation, buses B26 and B43 were found to have lowest index, indicating that they are the most critical buses and having more chances to voltage collapse. Hence, they are weakest buses to provide real and reactive power compensation support to a network for voltage profile improvement and power loss reduction.

III. POWER LOSS INDEX (PLI)

This approach is implemented for identifying suitable buses for placement of DG units and shunt capacitors and it is also helpful for shrinking the search space during optimization procedure. In addition, power flow calculations are required to calculate the loss reduction (LR) values by providing reactive power compensation at each bus, which is equal to a total reactive load of a network. At a time one bus is considered (Oladepo and Hasimah, 2019). The relation for evaluating PLI value of ith bus is formulated using (2).

$$PLI(i) = \frac{LR(i) - LR_{min}}{LR_{max} - LR_{min}} \quad (2)$$

Those buses which are having higher PLI values and system voltage below 0.95 pu are chosen as candidature buses for capacitor installation. These are the following steps for implementation of PLI approach to identify candidate buses for capacitor placement.

Step 1: Run load flow and compute real power loss.

Step 2: Provide reactive power compensation across each bus, which is equal to the total system reactive load of a network and then execute load flow program and evaluate system real power loss for all the buses except slack bus and store the values.

Step 3: Calculate LR = (Base case system active power loss – system active power loss obtained for each bus compensation) and store.

Step 4: Determine maximum and minimum LR. Then evaluate PLI values using (3.2). Sort these PLI values in descending order.

Those buses which are having higher PLI values and lower voltage under 95% are preferred as most suitable buses for placement of capacitor.

IV. POWER FLOW SOLUTION OF HILLTOP 11KV DISTRIBUTION NETWORK WITHOUT THE INTEGRATION OF DG UNITS OR CAPACITOR BANKS

Figure 3 shows the graphical representation of the voltage profiles of the buses in the distribution network while the Load flow in Hilltop 11kV network buses when DG units and Capacitor bank has not been installed is displayed on Figure 4.It is evident that from the result of the load flow analysis shown that the voltage profiles of majority of the buses are below the acceptable operational level while only few are at operating at normal voltage level. The buses with voltage profile below the acceptable range include IVA Pottery,PRODA, Ekeani Ngwo, St. Mary Ngwo, Ukaka etc. while the buses with voltage profile within the acceptable range of 10.45<kV>11.45 include Colliery Hospital IVA Valley,Copex IVA Valley,Radio Nigeria TX Ngwo, ATC Ngwo, Police Ngwo,Nursing Home Udi Siding etc.

Figure 5:

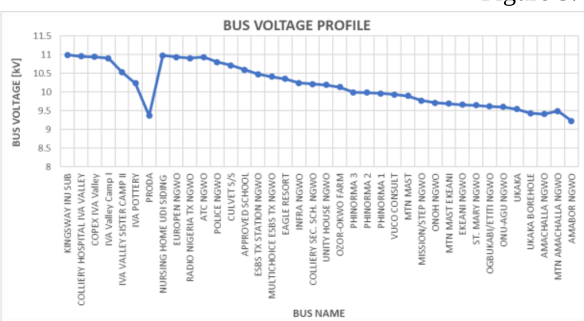


Figure 3: Voltage profile of Hilltop 11kV network without DG units and Capacitor bank installation

Figure 6:

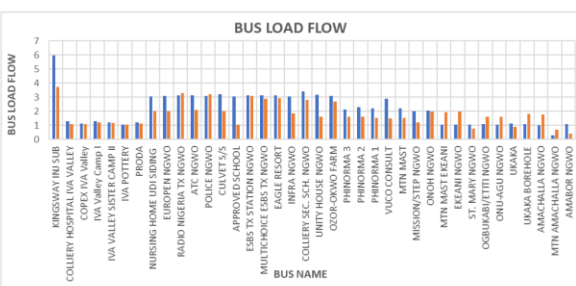
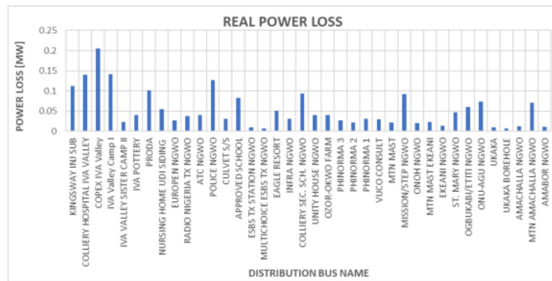
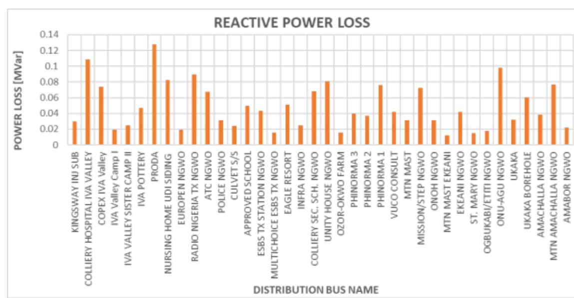


Figure 4: Load flow in Hilltop 11kV network buses without DG units and Capacitor bank installation

The active and reactive power losses on the distribution network buses is clearly shown in Figure 5 and 6 respectively. The total network active and reactive power losses in the radial distribution system were calculated as 2.018MW and 1.8362MVar respectively. The highest real power loss was recorded on COPEX IVA Valley bus (at magnitude of 0.206 MW) while the lowest real power loss was recorded on Multichoice ESBS TX Ngwo bus at magnitude of 0.0094MW). On the other hand, the highest reactive power loss was recorded on PRODA bus (at magnitude of 0.0816MVar) while the lowest reactive power loss was recorded on MTN Mast Ekeani bus (at magnitude of 0.062MVar).



Active Power Losses in the 11kV distribution network without DG units and Capacitor bank



Reactive Power Losses in the 11kV distribution network without DG units and Capacitor bank.

V. INTEGRATION OF DG UNITS IN 11KV DISTRIBUTION NETWORK

It can be clearly seen from Figure 7, that the 1.5MW DG units have impacted a compensation effect on the voltage profiles of the radial distribution network. The voltage profiles of majority of the buses that were below the acceptable operational level have been improved significantly except for Ogbukabi/Etiti Ngwo bus which was improved from 9.22kV to 10.41kV (still violating the 10.45<kV>11.45 voltage constraint). Figure 7 shows the graphical representation of the voltage profiles of the buses in the Hilltop 11kV network buseswhen only DG units were installed. The blue curve represents the base case which is the voltage profile of the network when no DG units or capacitor banks were installed while the red curve represents the voltage profile of the network when only DG units were installed. The average overall improvement in the voltage profile of the distribution network is calculated to be 5.12%.

However, it should be noted that a few buses did not receive any significant increment or reduction in their voltage profiles, though they are still within the acceptable operational range. These buses include Police Ngwo, COPEX IVA Valley and Colliery Hospital IVA Valley.

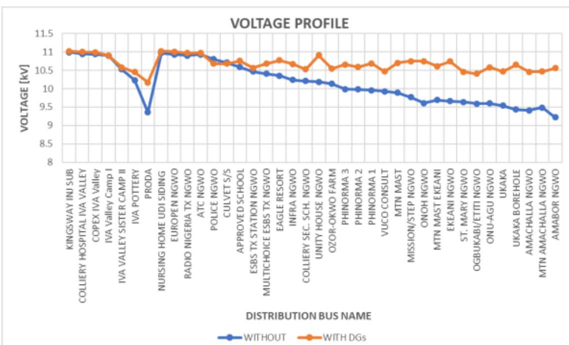
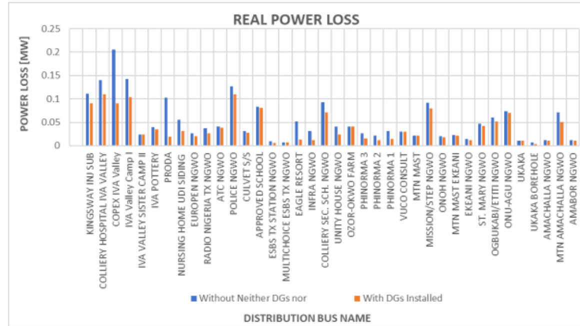


Figure 7: Voltage profile of Hilltop 11kV network with only DG units' installation

After the 1.5MW DG units were installed at buses B26 and B43, the active and reactive power losses on the distribution network buses was evidently reduced as depicted Figure 8 and 9 respectively. The blue bar represents the base case which is the losses in the network when no DG units or capacitor banks were installed while the red bar represents the losses in the network when only DG units were installed. As before, the total network active and reactive power losses in the radial distribution system were calculated as 1.458 MW and 1.2252 MVar respectively. The highest reduction in real power loss was recorded on COPEX IVA Valley bus (which was reduced from 0.206 MW to 0.0901 MW). On the other hand, the highest reduction in reactive power loss was recorded on MTN Amachalla Ngwo bus (which was reduced from 0.0507 MVar to 0.0085 MVar). The average overall reduction in the losses in the distribution network is calculated to be 27.75% for real power loss and 33.28% for reactive power loss.



Active Power Losses in the 11kV distribution network with only DG units installed

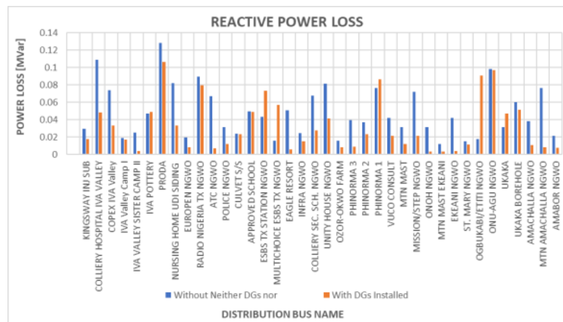


Figure 9: Reactive Power Losses in the 11kV distribution network with only DG units installed

VI. INTEGRATION OF CAPACITOR BANKS IN 11KV DISTRIBUTION NETWORK

Similarly, it can be clearly seen from Figure 10, that the capacitor banks have impacted a compensation effect on the voltage profiles of the radial distribution network. In this case, unlike the case of only DG units integration, almost all the voltage profiles of the buses that were below the acceptable operational level have been improved significantly. Figure 16 shows the graphical representation of the voltage profiles of the buses in the Hilltop 11kV network buseswhen only capacitor banks were installed. The blue curve represents the base case which is the voltage profile of the network when no DG units or capacitor banks were installed, the red curve represents the voltage profile of the network when only DG units were installed while the green curve represents the voltage profile of the network when only capacitor banks were installed. The average overall improvement in the voltage profile of the distribution network is calculated to be 5.70%.

However, it should be noted that a few buses did not receive any significant increment or reduction in their voltage profiles, though they are still within the acceptable operational range. These buses include IVA Valley Sister Camp II, IVA Valley Camp I and Police Ngwo.

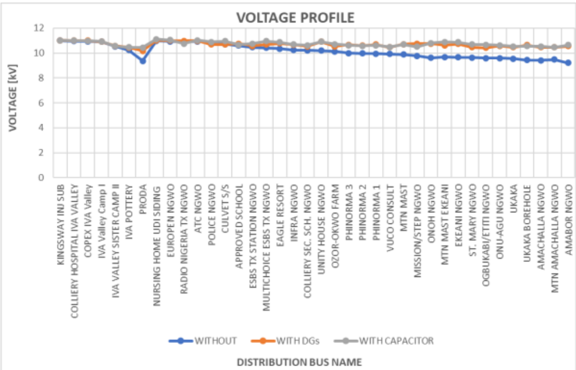


Figure 10: Voltage profile of Hilltop 11kV network with only Capacitor Banks installation

Following the VSI computation buses, B26 and B43 were found to have lowest index, indicating that they are the most critical buses and having more chances to voltage collapse. Hence, they are weakest buses to provide real and reactive power compensation support to a network for voltage profile improvement and power loss reduction. Capacitor banks were installed at buses B26 and B43, the active and reactive power losses on the distribution network buses was evidently reduced as depicted on Figures11 and 12 respectively. The blue bar represents the base case which is the losses in the network when no DG units or capacitor banks were installed, the red bar represents the losses in the network when only DG units were installed while the green bar represents the losses in the network when only capacitor banks were installed. As before, the total network active and reactive power losses in the radial distribution system were calculated as 1.4952 MW and 1.2435 MVar respectively. The highest reduction in real power loss was recorded on PRODA bus (which was reduced from 0.1022 MW to 0.0920 MW). On the other hand, the highest reduction in reactive power loss was also recorded on PRODA bus (which was reduced from 0.1281 MVar to 0.0208 MVar). The average overall reduction in the losses in the distribution network is calculated to be 25.91% for real power loss and 32.28% for reactive power loss.

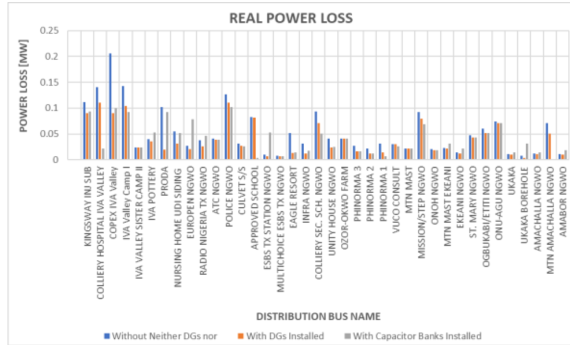


Figure 11: Active Power Losses in the 11kV distribution network with only capacitor banks installed

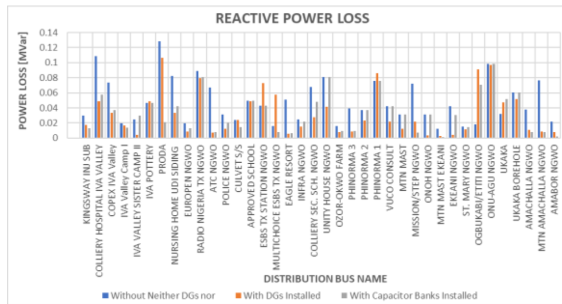


Figure 12: Reactive Power Losses in the 11kV distribution network with only capacitor banks installed.

VII. INTEGRATION OF BOTH DG UNITS AND CAPACITOR BANKS IN 11KV DISTRIBUTION NETWORK

It can be clearly seen from Figure 13, that the 1.5MW DG units and capacitor banks have impacted a compensation effect on the voltage profiles of the Hilltop radial distribution network. Here, the voltage profiles of all the buses that were below the acceptable operational level have been improved significantly and are no longer violating the 10.45kV<V>11.45kV voltage constraint. Figure 13 shows the graphical representation of the voltage profiles of the buses in the Hilltop 11kV network buses when both DG units and capacitor banks were installed. The blue curve represents the base case which is the voltage profile of the network when no DG units or capacitor banks were installed, the red curve represents the voltage profile of the network when only DG units were installed, the green curve represents the voltage profile of the network when only capacitor banks were installed while the purple curve represents the voltage profile of the network when both the DG units and capacitor banks were installed.

The average overall improvement in the voltage profile of the distribution network is calculated to be 6.09%. Integration of both DG units and capacitor banks in 11kV distribution network has shown better improvement in the voltage profiles and in loss reduction when compared to individual installations of DG units or capacitor banks.

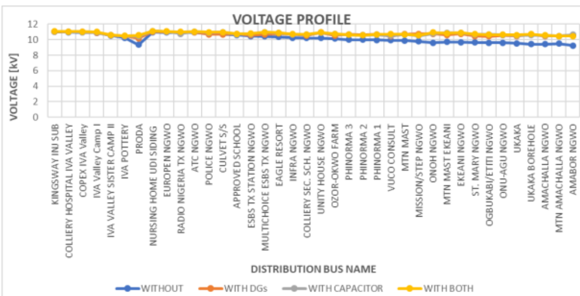


Figure 13: Voltage profile of Hiltop 11kV network with both DG units Capacitor Banks installations

Similarly, in this case, the active and reactive power losses on the distribution network buses was evidently reduced as depicted on Figures15 and 16 respectively. The blue bar represents the base case which is the losses in the network when no DG units or capacitor banks were installed, the red bar represents the losses in the network when only DG units were installed, the green bar represents the losses in the network when only capacitor banks were installed while the purple bar represents the losses in the network when both the DG units and capacitor banks were installed. As before, the total network active and reactive power losses in the radial distribution system were calculated as 1.2693 MW and 0.9190 MVar respectively. The highest reduction in real power loss was recorded on COPEX IVA Valley bus (which was reduced from 0.1422 MW to 0.0717 MW). On the other hand, the highest reduction in reactive power loss was also recorded on PRODA bus (which was reduced from 0.1281 MVar to 0.0201 MVar). The average overall reduction in the losses in the distribution network is calculated to be 37.10 % for real power loss and 49.95 % for reactive power loss.

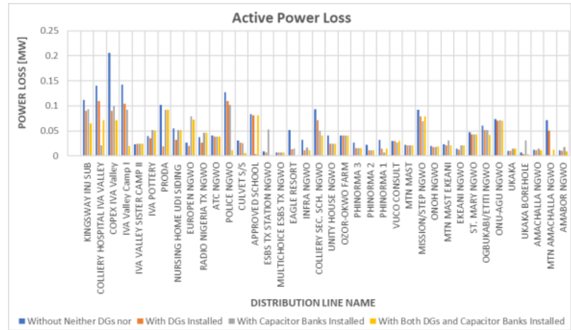


Figure 14: Active Power Losses in the 11kV distribution network with both DG units and capacitor banks installed

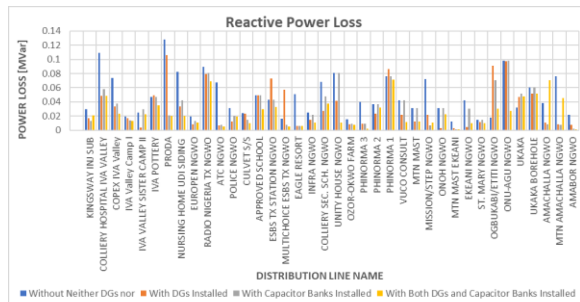


Figure 15: Reactive Power Losses in the 11kV distribution network with both DG units and capacitor banks installed

VIII. COMPARISON OF THE SIMULATION RESULTS

Table 1 shows the tabulation of the losses in the Hilltop 11kV distribution network when there is no DG units or capacitor banks installed on it. Also,with DG units, with capacitor banks and with both DG units and capacitor banks installed in it respectively. Table 2 shows the tabulation of the percentage improvements in loss reduction in the Hilltop 11kV distribution network. The graphical illustration is shown in Figure 16.

Table 1: Losses in the Hilltop 11kV Distribution Network

Parameter	Without both DG Units and Capacit	With DG Units	With Capacitor Banks	With both DG Units and Capacit

	or Banks			or Banks
Real Power Loss Reduction	2.0180 MW	1.4580 MW	1.4952 MW	1.2693 MW
Reactive Power Loss Reduction	1.8362 MVar	1.2252 MVar	1.2435 MVar	0.9190 MVar

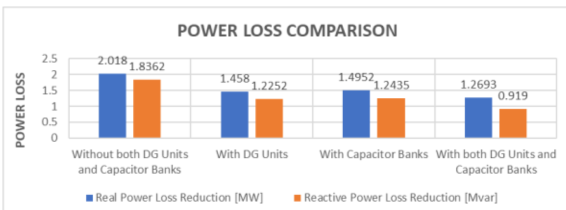


Figure 16: Losses in the Hilltop 11kV Distribution Network

From Figure17, it has been demonstrated vividly that the integration of both DG units and capacitor banks in 11kV distribution network has shown better improvement in loss reduction when compared to individual installations of DG units or capacitor banks.

Table 1: Percentage Improvements in Voltage profiles and Loss Reduction in Hilltop 11kV Distribution Network

Parameter	With DG Units	With Capacitor Banks	With both DG Units and Capacitor Banks
Voltage Improvement	5.12%	5.70%	6.09%
Real Power Loss Reduction	27.75%	25.91%	37.10%
Reactive Power Loss Reduction	33.28%	32.28%	49.95%

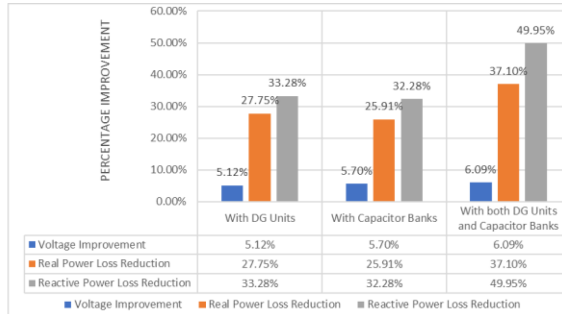


Figure 17: Percentage Improvements in Voltage profiles and Loss Reduction in Hilltop 11kV Distribution Network

CONCLUSION

In this paper, the VSI is successfully implemented for minimizing the total active and reactive power loss of the system through DG and shunt capacitor bank placement separately and simultaneously. These allocations are identified effectively via VSI and PLI approach. The validation of the proposed methodology is demonstrated on standard 38-bus Hilltop 11kV distribution network with three different load scenarios. In the four scenarios, case-4 (simultaneous installation of both DG units and capacitor banks) shows better results than the other two cases. From the outcomes, it is noted that the real and reactive energy loss reduction calculated in case-4 is 37.10% and 49.95% respectively which is better as compared to the other two cases which recorded 27.75% real power reduction and 33.28% reactive power reduction for case 2 (installation of only DG units) and 25.91% real power reduction and 32.28% reactive power reduction for case 3 (installation of only capacitor banks).

The proposed methodology is capable for solving this problem for voltage deviation and improvement in voltage profile. Similarly, case-4 (simultaneous installation of both DG units and capacitor banks) shows better results than the other two cases. From the outcomes, it is noted that the voltage profile improvement calculated in case-4 is 6.09% which is better as compared to the other two cases which recorded 5.12% improvement for case 2 (installation of only DG units) and 5.70% improvement for case 3 (installation of only capacitor banks).The optimal sizes of distributed generation and shuntcapacitor banks results realized from computation whenplaced individually and simultaneously on the distributionnetworks shows that power losses (active and reactive) caneffectively be reduced to a considerable extent as well asimproving the voltage stability profiles of the networks.

Again, simultaneous distributed generation and shuntcapacitor placement approach shows that a better powerloss reduction and voltage stability improvement can beobtained as compared to their individual placements andbase case values.

REFERENCES

[1] Ahmed Mohamed Azmy, E. E. (July 2005). Impact of distributed generation on the stability of electrical power system. *Power Engineering Society General Meeting, IEEE*.

[2] Lovins, (2002); Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size; Rocky Mountain Institute, 2002

[3] Mukul Dixit, Prasanta Kundu and Hitesh R. Jariwala, (2017). Incorporation of distributed generation and shunt capacitor in radial distribution system for techno-economic benefits. Engineering Science and Technology, an International Journal journal homepage: www.elsevier.com/locate/jestch. http://dx.doi.org/10.1016/j.jestch.2017.01.003.

[4] Murty, P. (2017). *Power Systems Analysis.* Oxford: Butterworth-Heinemann.

[5] Ogunjuyigbe A.S.O., A. T. (2016). Impact of distributed generators on the power loss and voltage profile of sub-transmission network. *Journal of Electrical Systems and Information Technology*, 94-107.

[6] Oladepo Olatunde and Awofolaju Tolulope Tola (2016). Power Quality Improvement in Electrical Distribution Network. American Journal of Engineering Research (AJER) e-ISSN: 2320-0847 p-ISSN: 2320-0936 Volume-5, Issue-12, pp-224-227 www.ajer.orgOladepo

[7] Pradeepa. H, Ananthapadmanabha T., Sandhya Rani D N, Bandhavya C (2015). Optimal Allocation of Combined DG and Capacitor Units for Voltage Stability Enhancement. *H. Pradeepa et al. / Procedia Technology 21 (2015) 216 – 223.* Published by Elsevier Ltd.

[8] Takahashi, et al, (2005); Policy Options to Support Distributed Resources; U. of Del., Ctr. for Energy & Env. Policy; 2005.

[9] Sujiang Peng, E. Z. (2018). Comprehensive evaluation of impacts of distributed generation integration in distribution network. *2018 Asia Conference on Energy and Environment Engineering (ACEEE 18)* (pp. 9-21). IOP.