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The Economics of Network Reconfiguration and Shunt Compensation on A 33 kV Distribution Network

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Abstract: This work studies the cost benefits derivable from network reconfiguration and shunt compensation of a Nigerian 33 kV distribution network. The approach adopted requires that the base case power flow analysis of the distribution network was first carried out, after which a shunt capacitor was used for compensation. The introduction of a tie-line in the network and a combination of capacitor and tie-line on same network were also carried out. The costs analysis of compensation and reconfiguration was carried out to understand their financial worthiness. The results obtained showed that the payback period (PP) for the introduction of compensation only, reconfiguration only and combination of compensation and reconfiguration are 1286.89 hr, 328.58 hr and 1043.31 hr, respectively. Though, reconfiguration only gives the least PP, a combination of compensation and reconfiguration has a long time cost benefit. At time above 5147.57 hr, it generates more profit than others.

Keyword: Reconfiguration, compensation, distribution network, payback period, cost of loss

1. Introduction

The frequent power outages experienced in developing Nations have reached such an unprecedented level that the public is suffering from electric power shortages. In most of these countries, power demands far exceed the available and installed capacities of the generating stations. For example, in Nigeria, a recent report estimated that Nigeria needs 30,000 MW of electricity generation to meet up with the current consumers' energy requirement, unfortunately, 28 power generation companies which currently operate below installed capacity collectively produce an average of 4000 MW (Izuora, 2022). In some instances, even if the generation is available, there exists weak transmission links to convey the energy to its destination. Regardless of how efficient the generation and transmission of electrical energy are, if the distribution networks (DN) are not well designed, the quality of energy delivered to consumers may be poor (Stevenson Jr & Grainger 1994). Parts of the major factors that most transmission and distribution systems suffer from are power loss and poor voltage profile. Most times, these are caused by outdated and weak system infrastructure, inadequate routine expansion and above all, improper planning. DNs are the closest to consumers, hence, its proper functioning will guarantee maximum customers satisfaction. In Nigeria, the DNs have three voltage levels of 33 kV, 11 kV, and 0.415 kV. Most industrial buildings are always powered by 33 kV and 11 kV, whereas residential buildings are powered by 0.415 kV three-phase or 0.24 kV single-phase (Lawal & Olasupo 2019). As stated earlier, improper planning before and after installation of distribution infrastructure contribute heavily to the problems being faced. One main tool that most power systems professional has been using for a very long time to plan is power flow analysis (PFA). PFA is a tool that is used to determine some steady state parameters of the system. The power-flow problem

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was first formulated in the late 1960s, and its main solution procedure was based on Newton–Raphson and Gauss–Seidel approaches (Tinney & Hart, 1967; Weedy et al., 2012). Although, these two methods are the most popularly mentioned in literature, Newton-Raphson is the most adopted. This is because of its sparsity, fast convergence and simplicity characteristics (Saadat, 2010). PFA gives an idea of what to anticipate in the system and the information derivable from PFA are used for necessary guidance. In some cases, PFA may reveal some weaknesses in the system. Real power loss and voltage magnitude limitation violations are some of the weaknesses that PFA has the ability to reveal (Komolafe & Lawal, 2015). However, these gaps can be corrected with necessary compensation (reactive supports) or reconfiguration (introduction of tie-line) of the system (Hung, Mithulananthan, & Bansal 2015; Magadum & Kulkarni 2020; Landeros, Koziel, & Abdel-Fattah 2019; Mahdavi et al. 2021).

Various works have adopted different methods to improve the performance of the distribution systems in Nigeria. While some adopted the inclusion of shunt capacitors in the systems, some used network reconfiguration. All of the works carried out confirmed the usefulness of shunt capacitor and network reconfiguration in performance improvement of the network. In the work of Abdulkareem et al., (2014), PFA analysis of a 33 kV DN of Abule-Egba in Southern Nigeria was carried out. The research used a computer-based model of an electrical distribution grid for simulation. The results of the analysis showed that 15 feeder pillars suffer low voltage violations. Shunt capacitors were used for their improvement and the introduction of capacitors resulted in a network with a better voltage profile and reduced losses. The PFA of a 33 kV network in Port-Harcourt was done by Idoniboyeobu & Ibeni, (2017) to identify buses with low voltages and subsequently injected reactive power to improve the voltage profile. The injection of reactive power (through shunt capacitor) reduced the power losses by 24.6 percent, and the bus voltage profiles were improved. The work of Emmanuel, Braide, & Idoniboyeobu, (2020) improved the low voltage profile of the 33 kV Old Airport feeders that supply electricity to Igwuruta, Port Harcourt with a shunt capacitor. The work of Peter, Benedict, & Chinweoke, (2022) further presents a heuristic technique for reducing power loss and improving the voltage profile of a 30 bus, 11 kV Onuiyi-Nsukka DN in Anambra. The DN is under the Enugu Electricity Distribution Company (EEDC). The least voltage magnitude in the network without compensation was reported to be 0.72 pu. However, a shunt capacitor of 1.2 MVAR was installed to keep the voltage magnitude within a limit of (0.95-1.05) pu. The shunt compensation was able to reduce the systems active and reactive losses by 55.56 % and 81.58 %, respectively. An improvement of the performance of the Iyowa Community 11/0.415 kV DN in Ovia North-East Local Government Area in Edo State was carried out (Agbontaen & Idiagi, 2021). The authors performed a loss sensitivity analysis on all the buses to determine the optimal location for the capacitor bank. The results obtained showed that the capacitor, indeed improved the voltage magnitude and reduced the system loss. A shunt capacitor of 1.2 MVAR was inserted in to the Enugu State, Nigerian Thinkers Corner DN by Peter, Benedict, and Ogbeide (2020) with great recorded improvements. The authors in Onodugo et al., (2022) used shunt capacitor on the 33/11 kV Enugu Metropolis Networks to reduce technical losses and as expected, the voltage profile was also improved alongside losses. The financial implication of the technical losses in the existing Asaba Government Core Area injection substation DN was estimated (Egwaile, Ogbeide, & Osahenvemwen, 2018). The authors reported that, the injection of 1.5 MVAR shunt capacitor significantly reduced the systems losses and improved the voltage profile. They further stated that, in 5 to 10 years, there would be significant savings in cost due to the reduction in losses incurred in the system. This will definitely increase the income of the distribution company serving the area. The techno-economic benefit derivable from the installation of shunt capacitor in a 34-bus Ayepe Nigerian DN was studied (Salimon et al., 2022). The results of the work showed that appropriate penetration of shunt capacitor in to the network leads to reduction of power losses, voltage profile improvement as well as cost reduction resulting in high net savings for the distribution company. The effect of optimal location of shunt capacitor in the same Nigerian network was investigated (Salimon et al., 2020). In the work, the authors placed one to three capacitors in the network using cuckoo search algorithm. The results of the study demonstrate that the method adopted is capable of saving significant cost in addition to reducing the total power loss and improving the voltage profile. Igunbor, Atuchukwu, & Iloh, (2019) performed an optimum capacitor placement based on genetic algorithm (GA) to achieve improved reactive power compensation on a DN of the Benin Electricity Distribution Company (BEDC) network. The authors optimally placed a shunt capacitor in the existing Asaba Government Core Area injection substation DN. The results obtained are similar to ones mentioned earlier with a presentation of a 10 years cost savings as a result of the compensation. It is important to note that, while the works in Abdulkareem et al.,; Idoniboyeobu & Ibeni,; Emmanuel, Braide, & Idoniboyeobu,; Peter, Benedict, & Chinweoke, ; Agbontaen & Idiagi,; Peter, Benedict, & Ogbeide,; Onodugo et al., (2014; 2017; 2020; 2022; 2021; 2020; 2022) only focused on the technical benefits derivable from the installation of shunt capacitor in the Nigerain DN, the works in Egwaile, Ogbeide, & Osahenvemwen,; Salimon et al.,; Salimon et al.,; Igunbor, Atuchukwu, & Iloh, (2018; 2022; 2020; 2019) discussed the techno-economic benefits of installing capacitor in the network. The techno-economic analysis further gives insight into the financial feasibility of the implementation of the proposed project.

As stated earlier, some works have adopted the use of network reconfiguration for the Nigerian DN. Some of these works are discussed as follows; a network reconfiguration of Port-Harcourt sub-distribution network was successfully carried out in Amesi, Bala, & Ibe, (2017) to improve the network's voltage profile. The effects of a combination of using distributed generation (DG) and network reconfiguration on a distribution network under the Jos Electricity Distribution Power Company Plc was examined (Babayomi, Babatunde, & Okharedia, 2018). The outcomes of the work show that network reconfiguration resulted in an improvement of the minimum voltage level by up to 1.2 %. In addition to the improvements in voltage levels, network reconfiguration was also reported to have reduced power losses. Akpojedje & Ogujor, (2021) proposed an optimal network reconfiguration for the Ugbowo 2x15 MVA, 33/11 kV DN to reduce the high system power losses, balance the feeders' load and improve the voltage profiles. The results revealed that the proposed technique optimally select the switches that produce the best configuration which gives minimum power losses, reduce the load balance index, balance the feeders' load and improve the system's voltage profile in most of the buses within acceptable limits. Akpojedje & Ogujor, (2019) applied a DN reconfiguration using Particle Swarm Optimization (PSO) for active power loss minimization and reliability improvement to solve the 11 kV Pama Distribution feeder in Ungwan Boro Injection sub-station located in the Southern part of Kaduna State. The results show that a power loss reduction of 57.15% was achieved with the optimal location of tie switches. The usage of political optimizer to optimally reconfigure the Ayepe 11 kV, 34-bus feeder of Ibadan Electricity Distribution Company (IBEDC) was carried out (Fajuke & Shoyoye 2022). The results show that there was a 12.86 % reduction in the total power loss after reconfiguring the Network.

It should be noted that all the works available in open literature only focused on the analysis of the technical benefits derivable from network reconfiguration and never investigated the economic benefits. Analysis of the economic benefits will inform the distribution company (DISCO) of the financial worthiness of network reconfiguration viz-a-viz the period required for return on investment (ROI). In this work, a comparative techno-economic analysis of the inclusion of shunt capacitor and reconfiguration of the Osogbo DN is presented and discussed. This network is operated and maintained by IBEDC, Ibadan. The analysis in this study involves three network improvement strategies: inclusion of capacitor only, reconfiguration of the network only and the combination of capacitor and reconfiguration.

2. Materials and Methods

The one-line diagram shown in Fig. 1 consists of interconnecting lines and buses of Osogbo 33 kV distribution network. The locations of the buses on a Google map are shown in Fig. 2. The square boxes and yellow lines on Fig. 2 are the exact locations of the buses and transmission lines, respectively. Names of the buses are shown in Table A1 of the appendix section. Osogbo is the Capital of Osun State, Nigeria and lies on coordinate 7.778 North and 4.553 East (Google Map, n.d). The DN is radial in nature and has 31 buses and 30 transmission lines. Overhead lines transport electric power from the 132/33 kV substation into the several 33 kV substations in the Osogbo DN. At the substations, the transformers are either 33/11 kV or 33/0.415 kV step down transformers.

In PFA, Equations (1) and (2) are the two main equations usually solved at each bus i. These equations are referred to as power mismatch equations. The number of these equations is dependent on the type of buses in the system. The known real and reactive powers (*P* and *Q*) on the system's buses determine the number of equations required. For instance, each load bus in the system generates two equations (i.e. *P* and *Q*), since the real and the reactive power are known at this bus. Also, each voltage-controlled bus generates one equation (i.e. *P*), since the real power is known at this bus. Equations (1 and 2) are non-linear, hence, it requires iterative methods of solving non-linear equations. Gauss-Seidel and Newton-Raphson methods are the most popular approaches to PFA, though, Newton-Raphson is mostly considered due to its good convergence characteristics. A robust solution procedure for both methods can be accessed in (Saadat 2010). A solution software based on NR had been developed by Saadat (2010) and it was found to be very effective in carrying out PFA. This software was adopted in this work. It should be noted that the base MVA used throughout this study was set at 100 MVA.

$$P_{gi} - P_{di} - \sum_{k=1}^{nb} V_i\, V_k\, Y_{ik} \cos(\boldsymbol{\delta}_k - \boldsymbol{\delta}_i + \boldsymbol{\theta}_{ik}) = 0 \quad (1)$$

$$Q_{gi} - Q_{di} + \sum_{k=1}^{nb} V_i\, V_k\, Y_{ik} \sin(\boldsymbol{\delta}_k - \boldsymbol{\delta}_i + \boldsymbol{\theta}_{ik}) = 0 \quad (2)$$

where

P_{di} and $Q_{di}$are, respectively, the active and reactive power demands at bus *i*.

P_{gi} and Q_{gi} are, respectively, the scheduled active and reactive power generations.

V_{it} and V_{kt} are the voltage magnitudes at buses *i* and *k*, respectively.

δ_{it} and δ_{kt} are the voltage phase angles at buses *i* and *k*, respectively.

Y_{ik} and θ_{ik} are, respectively, the magnitude and angle of the admittance of the line connecting buses *i* and *k* together.

nb is the total number of buses in the network.

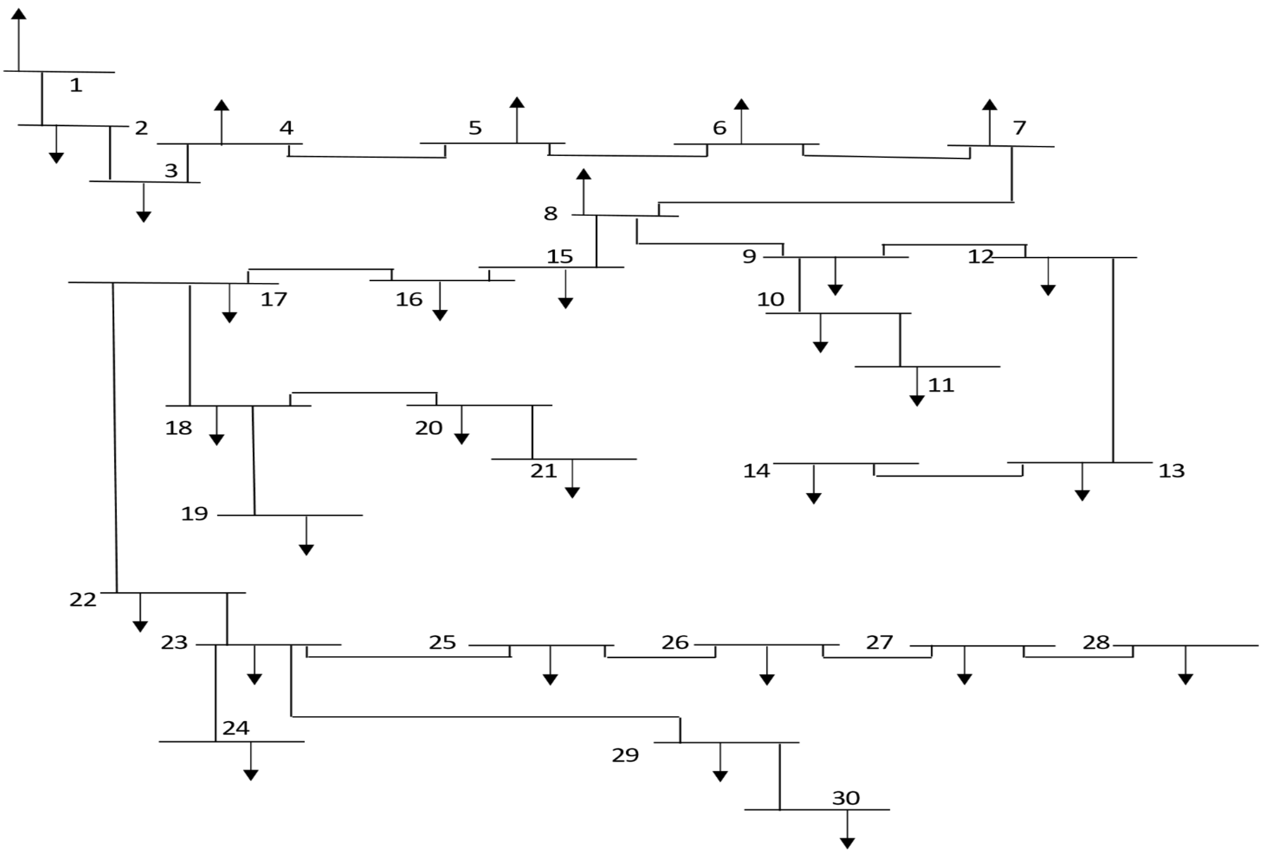

Fig. 1 – One-line diagram of Osogbo 33 kV DN

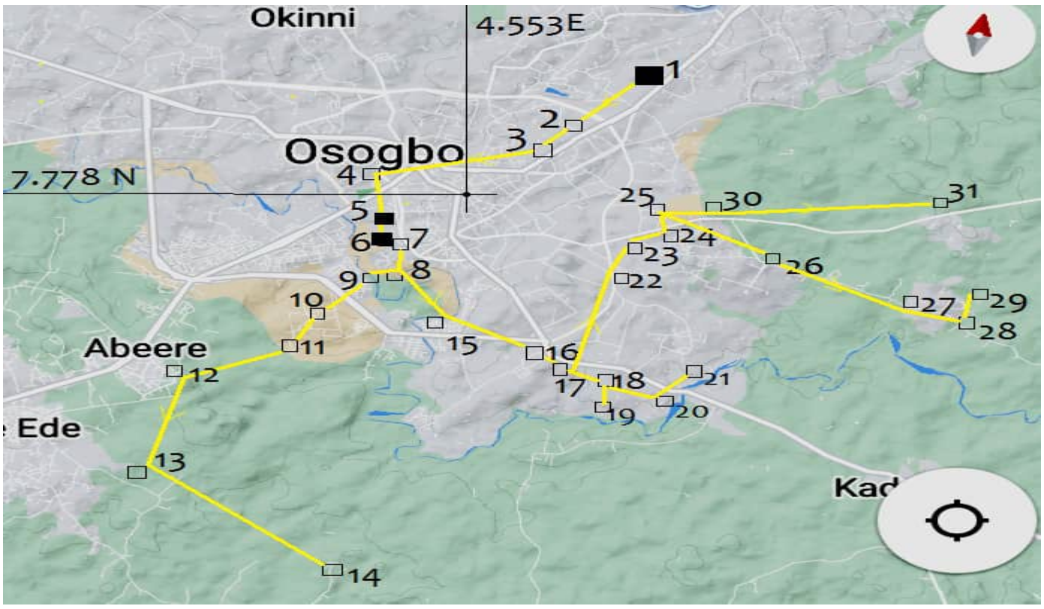

Fig. 2 - Google Map showing the locations of the buses in Osogbo (Google Map 2023)

For the investigation of the DN, the injection station is considered as the slack bus. The data needed for this software are the generator, lines, loads and bus parameters. All data were sourced from (Olasupo, 2012), where the load data was calculated using 100% loading of the transformers' installed capacities and an assumed power factor of 0.8. All the conductors used in the system are of 100 mm^2 size and the required table was used to calculate the line parameters. The true lengths of the lines were measured using the odometer of a motorcycle (Olasupo, 2012). It should be noted that, in this system, there exist a generator bus, which is the injection station. Key performance indicators (KPI) considered in this work are the voltage magnitude profile, total power generated, and total system losses.

This work considers four cases as follows;

A. The PFA of the DN was carried out without any compensation and reconfiguration
B. The PFA of the DN was carried out with shunt capacitor compensation only
C. The PFA of the DN was carried out with reconfiguration of the network only
D. The PFA of the DN was carried out with capacitor compensation and reconfiguration of the network only

The first scenario is the base case (i.e. case A), where the steady state of the network was studied without the inclusion of any compensation or reconfiguration. After the PFA for the first case, a trial by error experimentation was done by placing a capacitor bank of 20 MVAR on all buses and the mentioned KPI were recorded to identify the bus that returned the best KPI (Lawal & Olasupo, 2019). This bus was settled for as the best location for the capacitor. To reconfigure the network (for case C), the following procedures were followed;

i. From the base case results, identify the bus where the voltage magnitude starts to decrease below 0.9 pu.
ii. To reconfigure the network, disconnect this bus from the bus before it and reconnect it to bus 1 to form the tie-line. For example, if bus 5 is the bus to start with, line 4 to 5 is disconnected and line 5 to 1 forms the tie-line. This is illustrated in Fig. 3.
iii. Calculate the line parameters of the tie-line formed. This involves determining the length of the line. The length of the tie-line is an addition of all the length of lines before the bus being disconnected. For example, the length of tie-line 5 to 1 will be the addition of all previous lines before bus 5 (i.e. lines 1 to 2, 2 to 3, 3 to 4 and 4 to 5).
iv. Run the power flow software on the new system and record the KPI.
v. Repeat procedures i to iv with all the low voltage buses.
vi. From (i to v), the reconfiguration that gives the best KPI was noted and settled for. It is important to note that, due to cost implication of tie-lines, only one tie-line was considered for this study.

A capacitor of 20 MVAR was also used in the reconfigured network to further study the effects of installing a capacitor in the reconfigured network. The capacitor was placed on same location obtained for case B.

A comparison of the four cases was carried out to identify the approach that yielded the best performance. A cost analysis of the cases involving the modification of the network (i.e. cases B to D) was also carried out. This was done with a view to giving the DISCO an idea of the payback period (PP) and anticipated return on investments (ROI) made on the modifications presented.

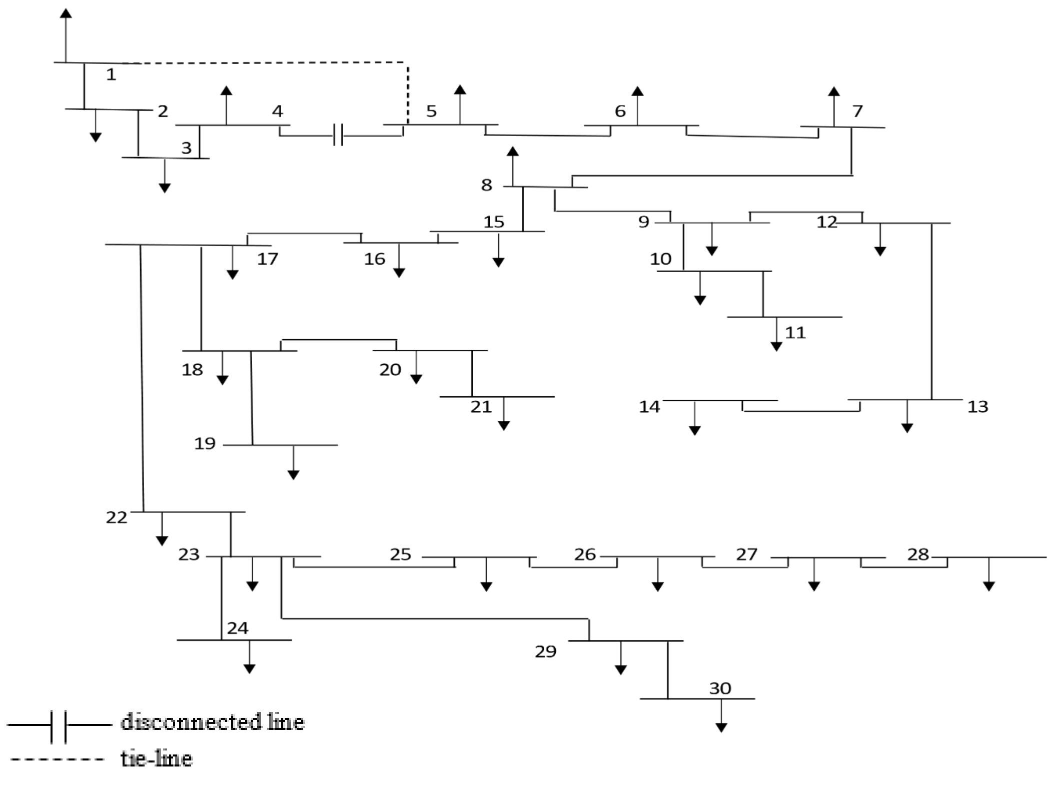

Fig. 3 - One-line diagram of Osogbo 33 kV with sample disconnected line and tie-line

3. Results and Discussion

This section presents the discussions of the results obtained from the PFA of the Osogbo 33 kV DN for all the cases earlier mentioned. Bus 1 was chosen as the slack bus and the voltage was set at $1.05\angle 0^0$ p. u. The results of concern here are the total real and reactive power generation, total real and reactive losses and the voltage deviations. The cost analysis of the considered cases is also presented.

3.1 Case A: Power Flow Solution Results without Compensation

The results obtained showed that the voltage magnitude on the buses after bus 5 (Odiolowo 1) fall below the tolerable limit of 0.90 p.u. The maximum and minimum voltage magnitudes obtained are, 1.05 p.u. and 0.8644 p.u., respectively. The total real and reactive power injection at bus 1 are 37.729 MW and 25.271 MVAR, respectively. Also, the real and reactive losses of the system are 7.049 MW and 2.261 MVAR, respectively. These values, respectively, amount to 18.68 % and 8.95 % of the real and reactive power injection.

3.2 Case B: Power Flow Solution Results with Compensation Only

As stated earlier, a trial by error experimentation was carried out on all busses with the inclusion of 20 MVAR worth of capacitor. This was done to identify the bus that gives the best performance in terms of voltage profile and system losses. The results of the experimentation showed that Odiolowo II (bus 6) gave the best performance out of the 31 buses. The location (bus 6) that returned the best performance of the system is an indication that, the reactive power deficiency starts from that point. Recall that bus 6 is the first bus with voltage magnitude violation. As expected, the system was improved and the maximum and minimum voltage magnitudes are 1.05 p.u. and 0.90 p.u. respectively. The real and reactive power injections are 35.090 MW and 4.424 MVAR respectively. The sharp drop in the value of the reactive power generation is as a result of the injected 20 MVAR by the capacitor. Likewise, the real and reactive losses of the system are 4.410 MW and 1.414 MVAR, respectively. These values are, respectively, 12.57 % and 5.79 % of the total injected real and reactive power. It should be noted that, the injected reactive power used in determining the percentage reactive loss considers the value of the capacitor's reactive power.

3.3 Case C: Power Flow Solution Results with Tie-Line Only

The line parameters of some of the tie-line that were experimented on this network are shown in Table 1. This table shows the disconnected line (DL), tie-line (TL), length of tie-line, total resistance (R) and reactance (X) of the tie-line (both in ohms and per unit). The base impedance (Z_b) used to determine the per unit values of line resistance and reactance was calculated to be 10.89 Ω. The resistance and reactance per kilometer of the conductor used are, respectively, 0.3928 Ω/km and 0.126 Ω/km (Olasupo, 2012). After the trial by error experimentation testing of various tie-lines as explained in Section 2, it was discovered that tie-line 7 to 1 gave the best results based on the considered KPI. The reconfigured network is shown in Fig. 4. To form line 7 to 1, line 6 to 7 was disconnected.

The power flow solution results obtained after reconfiguration shows that the maximum and minimum voltage magnitudes are 1.05 p.u. and 0.9637 p.u., respectively, total real and reactive power at injection station are 33.937 MW and 24.055 MVAR, respectively. The real and reactive losses of the system are 3.257 MW and 1.045 MVAR, respectively. The percentage losses are 9.60 % and 4.34 % for real and reactive power respectively.

Table 1 - Calculated parameters for tie-line only

S/No	DL	TL	Length (km)	R (Ω)	X (Ω)	R (pu)	X (pu)
1	4 - 5	5 – 1	10	3.928	1.26	0.3607	0.1157
2	5 - 6	6 – 1	10.1	3.9673	1.2726	0.3643	0.1169
3	**6 - 7**	**7 - 1**	**10.2**	**4.0066**	**1.2852**	**0.3679**	**0.118**
4	7 - 8	8 - 1	11.2	4.3994	1.4112	0.404	0.1296
5	8 - 9	9 – 1	11.6	4.5565	1.4616	0.4184	0.1342
6	9 - 10	10 - 1	14.1	5.5385	1.7766	0.5086	0.1631
7	10 - 11	11 - 1	14.4	1.8144	1.8144	0.5194	0.1666

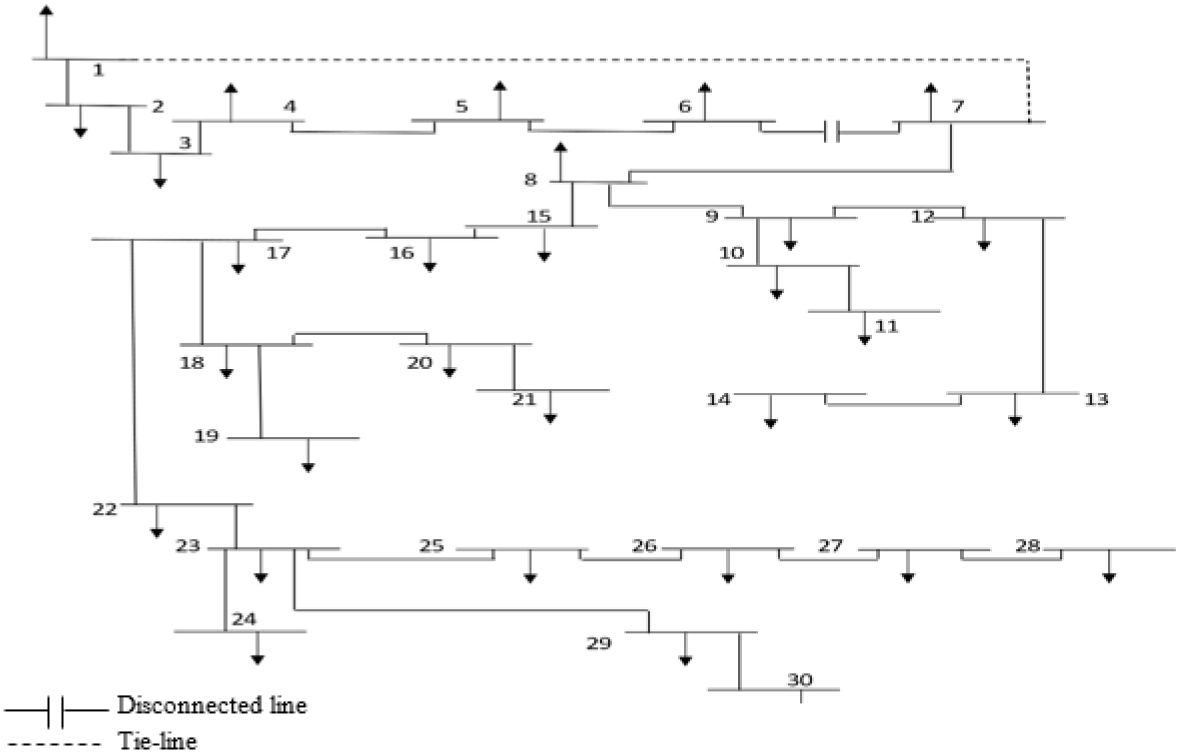

Fig. 4 - One-line diagram of the reconfigured Osogbo 33 kV DN

3.4 Case D: Power Flow Solution Results with Tie-Line and Compensation

The power flow solution results obtained with tie-line 7 to 1 and capacitor of 20 MVAR at Odiolowo II show that the maximum and minimum voltages are 1.05 p.u. and 0.9678 p.u., respectively, total real and reactive power at injection station are 33.279 MW and 3.844 MVAR, respectively. Also, the real and reactive losses of the system are 2.599 MW and 0.834 MVAR respectively. These losses amount to 7.81 % and 3.50 % of the real and reactive power at the injection station.

3.5 Comparison of Results

This section compares the results obtained for some major parameters of the network. The parameters compared are the voltage magnitude profile, total real and reactive power generated and real and reactive power losses. Fig. 5 shows a comparison of the minimum voltage magnitude for all the cases. It is glaring that case D gave the best voltage profile, followed by case C. the minimum voltage magnitude of case A was improved by 4.12 %, 11.49 % and 11.96 % for cases B, C and D, respectively. A comparison of the buses voltage profile for all cases is shown in Fig. 6. The real power injection at bus 1 for all cases was compared and this comparison is shown in Fig. 7. This figure also contains a comparison of the system real loss for the cases considered. The injection power needed to satisfy same amount of loads reduced in cases B to D, with case D having the least, closely followed by case C. The implication of this is that, the DISCO pay less amount of money for the purchase of energy to satisfy her customers' demands. When compared to case A, the percentage reductions in the real power injection for cases B, C and D are 7 %, 10.05 % and 11.79 % respectively. Also, the percentage reductions in the real power system loss for cases B, C and D are, 3.74 %, 53.76 % and 63.12 % respectively. Fig. 8 compares the percentage system loss for the cases considered. The trends of how best the cases performed remain the same.

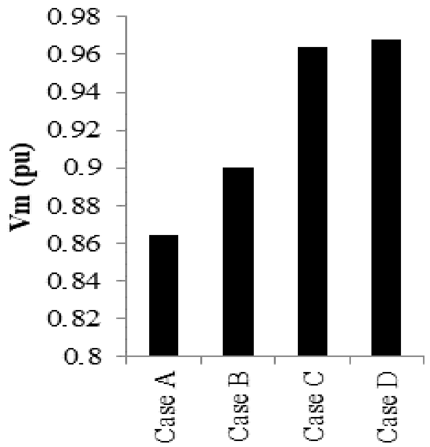

Fig. 5 - Minimum voltage magnitude for all cases

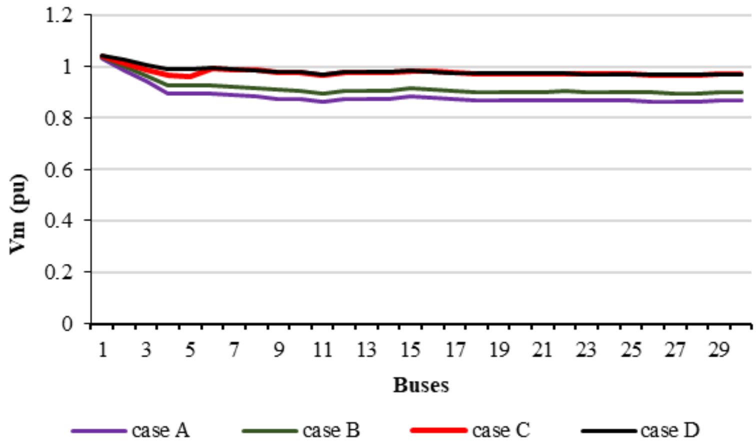

Fig. 6 - Voltage magnitude profile for all cases

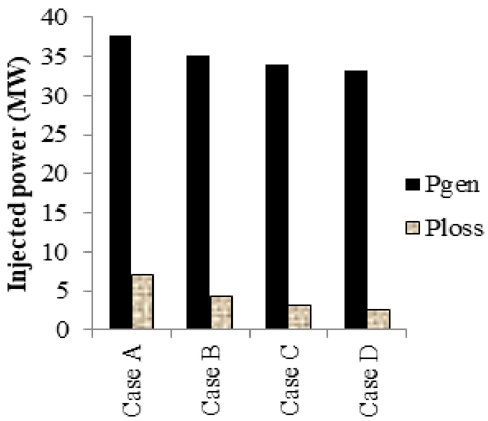

Fig. 7 - Injected real power and system active loss for all cases

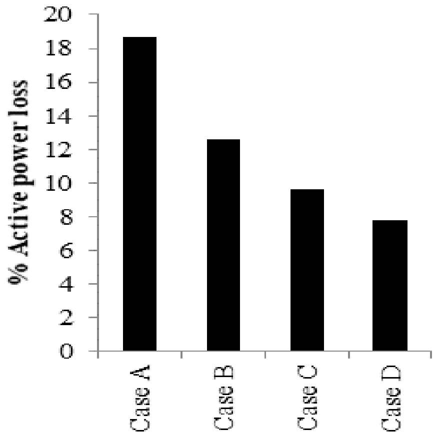

Fig. 8 - Active loss as a percentage of total injection power for all cases

3.6 Economic Analysis of the Modified Network

This section presents the cost implication for cases B, C and D while also discussing the cost benefit derivable from them. The works of Salimon et al.,; Okelola et al., (2020; 2022) were relied upon for the estimation of the installation cost of a capacitor bank. Table 2 shows that the cost for installing 20 MVAR (for case B) is two hundred and sixteen million, seven hundred and twenty thousand naira (₦216,720,000.00/$481,000.00). Four hundred and fifty naira (₦450) to a dollar was considered for this study. The bill of engineering measurement and evaluation (BEME) for the cost of installing new overhead line is shown in Table 3. From Table 3, the cost implication for 1 km overhead line for the new tie-line is seven million, seven hundred and eighty-eight thousand, One hundred and sixty naira (₦7,788,160.00/$17,307.02). For the selected tie-line, the length of line needed is 10.2 km as shown in Table 1, so, the total cost for reconfiguration (for case C) is seventy-nine million, four hundred and thirty-nine thousand, two hundred and thirty-two naira (₦79,439,232.00/$176,531.63). The total cost needed for case D is two hundred and ninety-six million, one hundred and fifty-nine thousand, two hundred and thirty-two naira (₦296,159,232.00/$658,131.6).

Table 2 - Installation cost of capacitor bank

S/No	Item	Cost ($)	Cost (₦)
1	20 MVAR Capacitor	480,000	216,000,000
2	Installation	1600	720,000
3	Total	481,000	216,720,000

Table 3 - BEME for installing 100 mm^2 over-head line per kilometer

S/ No	Material	Actual Qty	Unit Cost (₦)	Amount (₦)
1	RC Pole (33ft)	24	75,000.00	1,800,000.00
2	33kV Galvanized Steel X-Arm	18	12,000.00	216,000.00
3	Cutting and drilling	6	3,500.00	21,000.00
4	33kV Tie strap	36	2,400.00	86,400.00
5	33kV Long rod	36	8,000.00	288,000.00
6	33kV Pin Insulator (Si)	58	8,000.00	464,000.00
7	Tension set	54	7,000.00	378,000.00
8	Stay Set with Cement Block	18	12,500.00	225,000.00
9	5/8X12" Bolt & nut	24	1,000.00	24,000.00
10	5/8X9" Bolt & nut	23	400.00	9,200.00
11	5/8X8" Bolt & nut	50	400.00	20,000.00
12	5/8X2" Bolt & Nut	46	300.00	13,800.00

13	5/8 GI Round Washers	50	100.00	5,000.00
14	100mm^2 Aluminum conductor (ACSR)	3080	980.00	3,018,400.00
15	100mm^2 full current Aluminum line tap	6	2,000.00	12,000.00
16	25mm^2 GI Earth Rod	4	3,500.00	14,000.00
17	Installation and Transportation	1	650,000	650,000.00
	Total			7,244,800.00
	Value Added Tax (7.5%)			543,360.00
	Grand Total			7,788,160.00

The cost analysis for all cases is shown in Table 4. The energy tariff used for this study is ₦63.79/$0.412 per kWh of electricity (Ofikhenua, 2022). This amount was the least announced for IBEDC by the National Electricity Regulation Commission (NERC). This amount had been in place since year 2021. The power gain (PG) derivable from cases B to D with respect to case A are 2.64 MW (7.05 - 4.41), 3.79 MW (7.05 - 3.26) and 4.45 MW (7.05 - 2.60), respectively. Table 4 also shows the amount wasted due to power loss (i.e. cost of loss) per hour for different cases. As expected, case D, with the least power loss has the least cost of loss of ₦165,854.00/$368.56 per hour. The per hour cost of loss was calculated by multiplying the active loss (P_{loss}) by the electricity tariff. In comparison to case A, the savings per hour obtained for cases B to D are as shown in the table. The savings were calculated by subtracting the cost of loss for cases B to D from that of case A (base case). Case D saved the network the sum of ₦283,865.50/$630.81 per hour. Based on the cost of installation for cases B to D (as shown in tables 2 and 3), the payback period (PP) are 1286.89 hr, 328.58 hr and 1043.31 hr, respectively. The implication of these values is that, after the stated period, the DISCO begins to make profit from the investment made on improving the network. Though, case C might have the least PP, the longtime cost benefit of case D is the best. An equation to determine loss/profit as a function of time for the cases considered is shown in eq. (3) and a graph that depicts this equation is presented in Fig. 9. It is important to note that the negative and positive cost values in the figure indicate loss and profit. At 5147.57 hr, cases C and D will generate equal amount of profit as shown in Fig. 9. Immediately the time exceeds 5147.57 hr, case D starts to generate more profit.

Table 4 - Cost analysis for different cases

Cases	P_{loss}	PG	Per hour cost of loss (₦)	Per hour savings (₦)	PP (hr)
A	7.05		449719.5		
B	4.41	2.64	281313.9	168405.6	1286.89
C	3.26	3.79	207955.4	241764.1	328.58
D	2.6	4.45	165854	283865.5	1043.31

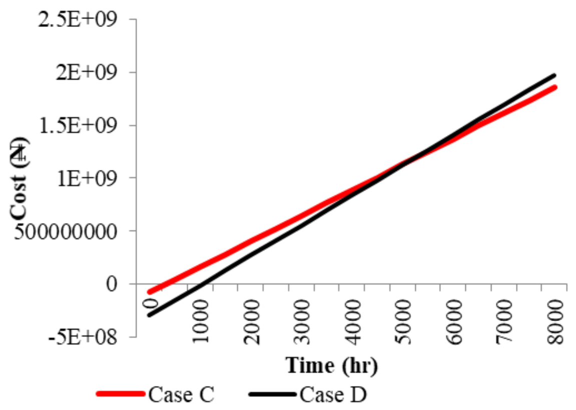

Fig. 9 - Profit and loss analysis for cases C and D

$$POL = ST - I \tag{3}$$

Where *POL* is the profit or loss derivable from the network modifications, *S* is the savings per hour as shown in table 4, *T* is the time (in hour) and *I* is the initial investment.

4. Conclusion

The modification of the Osogbo 33 kV DN has been carried out with the inclusion of shunt capacitor and tie-line (for reconfiguration). These two tools have been used separately and simultaneously for the analysis carried out. As expected, the modifications improved the network's performance in terms of voltage profile and system loss. The cost analysis of these modifications was also done. The results obtained showed that the system performed best with the combination of tie-line and shunt capacitor. Though, this modification comes at a very high cost, the long term cost benefits outweigh the investment cost. These benefits are as a result of the drastic reduction of system active loss by 63.12 percent when compared to base case loss. The corresponding cost of this loss reduction is highly significant. Further work can consider the economics of a DN with the simultaneous inclusion of distributed generation (DG), tie-line (for network reconfiguration) and shunt capacitors.

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Appendix A: The description of the Osogbo DN is shown in Table A1.

Table A1 - Description of Osogbo 33 kV DN buses

Bus number	Bus name
1	Injection sub-station
2	Deeper Life
3	SIB
4	Tinumola
5	Odiolowo 1
6	Odiolowo 2
7	Auxiliary
8	Asubiaro
9	UNIOSUN TH
10	Fountain University
11	M/Works
12	Abere
13	Garri Processing
14	Ajenisua
15	Lasinmi
16	OkeIjetu
17	MTN
18	NULGE
19	Crownfield
20	Owode
21	F/G/H
22	Sussy
23	Sawmill
24	Oduoye
25	Kasmo
26	UNIOSUN
27	Coker 1
28	Coker Village
29	Coker 2
30	OSBC
31	Egbeda