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Evaluating Technical Losses Arising from Power Factor Fluctuations: A Case Study of the Nekpenekpen 33/11 kV Injection Substation

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Abstract

In electrical power systems, losses occur as a result of various factors, both internal and external. These losses contribute to increased operating costs for electric utilities and higher energy expenses for consumers. Therefore, minimizing these losses is crucial due to its significant socioeconomic and financial implications for customers, utility companies, and the overall country. This study investigates the effects of power factor variations on inherently caused losses. The study involves analyzing the power loss parameters of a specific section in the Nekpenekpen 33/11 kV power distribution network, which is owned by the Benin Electricity Distribution Company (B.E.D.C.). It examines how changes in power factor affect the overall losses experienced within the network. This analysis is conducted by simulating the network using MATLAB/Simulink work tool. By employing variable loads, obtained results indicated that the connection of a load in a network can lead to a low power factor at a specific point. Additionally, the findings demonstrated that this low power factor at a particular point does not impact the magnitudes of power factor and load loss observed at other points within the network, leading to the recommendation for the implementation of a dynamic variable capacitor bank to enhance power factor at various levels of reactive load in a network.

1. Introduction

Electricity is a vital resource that is currently indispensable in homes and industries. Whether it comes from the grid system or it is self-generated, virtually all appliances used in the industries, offices and homes are powered by electricity. Though self-generation of electricity is good, the high initial cost of installation and also high operational costs has pushed vast number of end-users to connect to the electrical grid. The Electricity generated at the power stations is wheeled to the end user using transmission and distribution networks. Studies have shown that the receiving end electrical energy in an electrical network is usually lower than the sending end energy.

There are two distinctive types of electrical energy loss viz: technical and non-technical losses. Technical losses are due to energy dissipated in the conductors, equipment used for transmission line, transformer, sub-transmission line and distribution line and magnetic losses in transformers, and directly depend on the network characteristics and the mode of operation. A greater part of losses in a power system is recorded in primary and secondary distribution lines [1].

Ideally, the losses in distribution systems should range from 3% to 6% relative to the injected energy. However, in developed countries, these losses typically hover around 10%, whereas in developing countries, the losses can reach an average of approximately 20% [2], or even more. Consequently, it is crucial for electric utilities to reduce these percentages by enhancing the electrical network. This reduction in losses not only leads to increased profitability in the business but also enables the enhancement of service quality offered to consumers [3].

Non-technical losses encompass losses arising from meter defects, meter reading errors, inadequate billing for customer energy consumption, administrative shortcomings, financial limitations, estimates of unmetered energy supply and energy theft. These losses constitute 16.6% of the total losses observed in the transmission and distribution of electricity [4].

1.1 Examination of power system technical losses

Technical losses result from equipment inefficiency, inherent characteristics of the materials used in the lines and equipment and the sizes of lines and equipment. The three major contributors are the current squared losses through a resistance, transformer excitation losses and line and insulation corona or leakage losses [5]. In AC systems, the copper losses are higher due to skin effect. This effect leads to a higher flux density at the center of the conductor, causing a greater flow of current toward the surface. Consequently, the skin effect increases resistance and subsequently power loss. The increase in resistance is directly proportional to the frequency of the AC signal. Transformer losses consist of copper losses resulting from the internal impedance of transformer coils and core loss. Power transformers remain permanently connected to the power system, necessitating the consideration of their no-load losses. No-load losses depend on factors such as lamination type, core material, insulation, voltage and frequency. The most prevalent no-load losses are core losses, which comprise hysteresis and eddy current losses and are expressed as shown in Eqn. 1 and Eqn. 2 [5];

Hysteresis loss, $P_H = K_h f B_m$ (1)

Eddy Current Loss, $P = K_e f^2 B_m^2$ (2)

Where,

f = frequency, B_m = flux density of the core material, K_h, K_c = Hysteresis and Eddy current constant.

Dielectric losses refer to the dissipation of energy as heat in the dielectric material positioned between conductors. This heat is then dispersed into the surrounding medium. Induction and radiation losses, on the other hand, stem from electromagnetic fields surrounding the conductors. Induction losses occur when the electromagnetic field surrounding a conductor interacts with another line or metallic object, inducing current in that object. Consequently, power is dissipated in the object and lost [6]. Radiation losses arise when certain magnetic lines of force generated around a conductor fail to return to the conductor during alternating cycles. Instead, these lines of force are projected into space as radiation, resulting in power losses. In other words, power is supplied by the source but is not available to the load.

Distribution lines experience losses as a result of thermal effect of flow of current in the conductors. Technical losses can be evaluated through load flow study in line with parameters of equipment. For instance, the sum of losses in the wires of a three-phase balanced distribution system is expressed in Eqn. 3 [7];

$$P_L = \frac{2P^2 \rho l}{3aV_m^2 cos^2\varphi} \quad (3)$$

P_L= power loss in the 3 line conductors, P = transmitted power, ρ = resistivity of the conductor material, l = line length, a = cross-sectional area of the conductor, V_m = peak phase voltage, cosφ = power factor

The loss and load factor are common indices for assessing technical losses. In general, loss factor cannot be expressed in terms of load factor. However, the limiting values of the relationship may be established as illustrated in Eqn. 4;

$$Load\ Factor, LDF = \frac{Average\ demand\ over\ designated\ period\ of\ time}{Peak\ load\ occuring\ in\ that\ period} \quad (4)$$

$$Loss\ Factor, LSF = \frac{Average\ (load)^2}{Maximum(load)^2}\ \ or\ \ \frac{Average\ loss}{Peak\ loss}$$

1.2 Power Factor Correction

Technical losses can be reduced by improving the power factor. To correct a given power factor from $\cos\theta_1$ to an improved power factor$\cos\theta_2$, at an active power, P (kW), requires a capacitor of reactive power rating. Eqn. 5;

$$Q_C = P(tan\theta_1 - tan\theta_2)kVAr \quad (5)$$

Power factor correction can be carried out at different levels such as; correction by the manufacturers of electrical apparatus, correction by the supply utility and correction by the consumer,

Generally, figures in the range of 0.85 to 0.90 pf are taken as acceptable power factor levels before penalties are applied. It is important not to overcompensate when applying power factor correction capacitors since this could lead to an increase in receiving end voltage outside desirable limits. Typically, a power factor of approximately 0.95 is an acceptable limit to aim for.

1.3 Related studies

Undoubtedly, intense research works have been done and are still ongoing on the causes and reduction of losses in electricity transmission and distribution. Having a power factor close to unity or at unity is crucial, whereas a low power factor results in an increased demand for apparent power drawn from the power distribution.

According to Electricity distribution loses report, technical losses represent 6-8 % of the cost of generated electricity and 25% of the cost to deliver the electricity to the customer. A reduction in technical losses will originate two important savings: a decrease in energy required to be generated and a decrease in the maximum demand [8].

In [9], mathematical analysis of losses that occur in electric power system was explored. The author achieved that using Depezo loss formula, loss factor, system parameter for evaluating the system losses, differential power loss, power flow method, B-losses coefficient. Moreover, independent assessment of means of reducing technical losses is carried out in a given distribution network in [10]. The authors carried out their investigation on Mazoon Electricity Company and found that high number of substations and feeders are non-compliant with the Distribution System Security Standard, as regards technical losses. Among the loss minimization technique proffered in that research work are feeder reconfiguration, introduction of distributed generation (DG), and installation of capacitor banks.

Five strategies for diminishing technical losses were studied [11]. These approaches encompassed the re-conducting of networks, installation of voltage regulators, utilization of express feeders, implementation of high voltage distribution systems (HVDS), and establishment of new substations. Methodology for management of distribution system for loss reduction by network reconfiguration was outlined in [12].

Reviewed literatures showed that the main factor that affects technical loss is the quality of material used, fabrication and interconnection of equipment/materials used in transmitting and distributing electricity to the end-user. This implies that technical loss is a function of the electrical structure found in a location. Least discussed factor that causes power losses in a network is low power factor. Low power factor can be caused by the reactive elements in the transmitting/distribution network or the nature of the load connected to the network. More so, the problem this research will solve is to evaluate technical losses caused by power factor variations in a conventional electrical network using Nekpenekpen 33/11KV Distribution network as a case study.

2.0 Materials and method

The research is implemented by selecting a section of Nekpenekpen 33/11KV Distribution network which suits the study. Industrial feeder that feeds Industrial Steel Company and an Aluminum processing company was selected. The network parameters were simulated in MATLAB/Simulink environment. It was assumed that the net load of the Aluminium Processing Company which is predominately inductive varies. That variation induces variable power factor at the company's point of common coupling. Hence, the effect of the power factor variation on the power losses in the network is studied.

2.1 The network topology

The Nekpenekpen 33/11 kV Injection Substation at 2nd East Circular, Benin City, is a typical example of the primary distribution substation. The source of electric supply of Nekpenekpen Injection Substation is the 33 kV feeder from 330/132/33 kV transmission substation along Benin Sapele highway in Benin City.

The Nekpenekpen 33/11 kV, 2x7.5MVA injection substation is the sole source of electricity power supply to Nekpenekpen and its environs with four (4) outgoing feeders namely, Feeder 1, Feeder 2, Feeder 3 and Feeder 4. Two of the feeders are each connected to each of the two 7.5 MVA transformers. Transformer T1 at peak carries a maximum load of 600 A with Feeders 1 and 2 attached, while Transformer T2 has maximum load of 600A with Feeders 3 and 4 attached. Each transformer and feeder have its own associated relays and CTs for protection and metering purposes. The rating of the CTs is 600/1 A and the rating of the VTs is 33000/330 V.

Feeder 1 supplies electricity to residents and customers around MM Way, Akpakpava by Igbesamwan, Ikpoba Slope by Crystal Motors, parts of Dawson up to Lapo Microfinance Bank and its environs.

Feeder 2 supplies electricity to residents and customers around Second East Circular Road by Esin, Esigie police Road by First East Circular and also Old western road.

Feeder 3 supplies Electricity to residents of Nekpenekpen towards First East Circular road, Igbesamwan Road, parts of Akpakpava road up to the BEDC head Office, Sokponba Road from First East Circular to Kings Square and up to Mobil filling Station.

Feeder 4 supplies electricity to residents and customers around Eweka Area, MM way by Sapele Road, Second East Circular from Nekpenekpen to sapele road, First East Circular to Sapele road and parts of upper Sokponba Road. The illustration of the network is as shown in Figure 1.

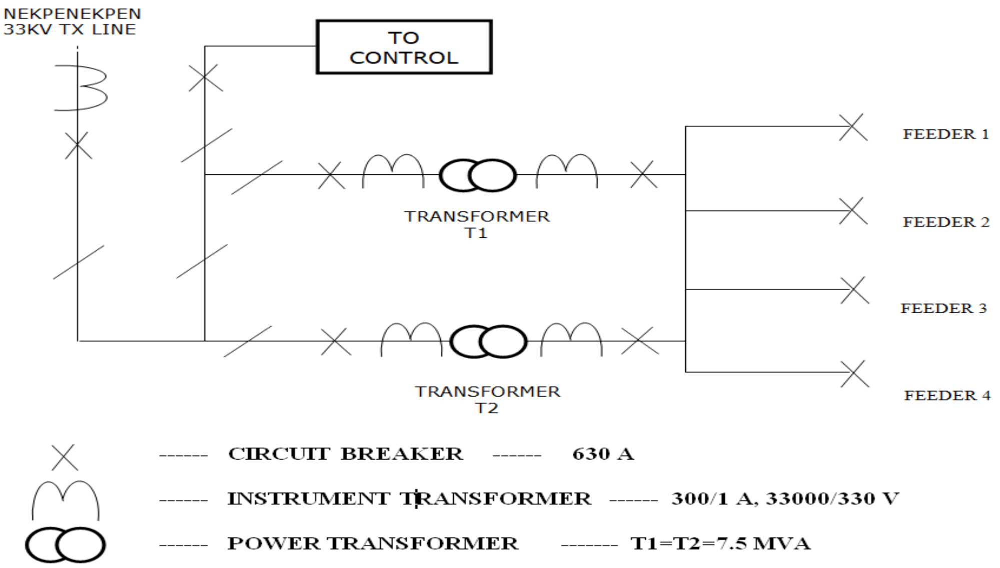

Figure 1: One line diagram illustrating the network

2.2 Data obtained from injection substation

Table 1 shows the obtained data from the injection substation.

Table 1: Data obtained from the injection substation

Rating of Transformer	7.5MVA*2
Number of Outgoing Feeders	4
Current Rating	600/1A
Voltage Rating	33000/330V
Length of Feeder	3.94kM

2.3 Modeling with MATLAB/Simulink

The practical network was modeled and simulated using different block sets found in MATLAB/Simulink environment. To comply with industry practice, the resistance and inductances per unit (pu) based on the transformer rated power (P_n in VA) and nominal voltage of the winding (V_n inV_{rms}) must be specified. The base resistance and inductance are defined in Eqn. 6 and Eqn. 7 respectively;

$$Rbase = 1\,pu = \frac{(V_n)^2}{P_n} \tag{6}$$

$$Lbase = 1\,pu = \frac{Rbase}{2\pi f_n} \tag{7}$$

It was earlier indicated that the resistive power loss in a cable is given by

$$P_{loss} = I^2 R \tag{8}$$

The theoretical plot of Eqn. 8 at constant resistance R is a parabola on top of horizontal axis.

2.4 Simulation model

As discussed earlier, the magnitude of current flowing through a network branch influences the losses incurred in the branch. This is demonstrated in a practical network located in Nekpenekpen distribution network. A branch of the network was simulated using Simulink environment in MATLAB. The one-line diagram of the network is shown in Figure 1 above while the simulated network is shown in Figure 2.

The branch of the network used in carrying out the research feed predominately a resistive load (electric arc furnace) through a 33kV/415V step-down transformer. However, the feeder also supplies an Aluminum processing company (AGEN Aluminum plc.) that uses many three-phase induction motor. As expected, the company's load is inductive and was represented as Load 1 in Figure 2. The parameters of the major components of the network used in the simulation are summarized in Table 2.

Table 2: Parameters for the components used in the simulation

	PARAMETER	**VALUE/UNIT**
Line 1	Type	π-section
	Resistance	0.5568Ω/km
	Inductance	1mH
	Capacitance	0.22nF
	No. of Sections	10
	Length	50km
Line 2	Type	π-section
	Resistance	0.5568Ω/km
	Inductance	1mH
	Capacitance	0.22nF

	No. of Sections	10
	Length	10km
Transformer	No. of Phases	3
	Power Rating	1MVA
	Voltage Level	33kV/415V
	Primary/Secondary resistance	0.002/0.002 pu
	Primary/Secondary Inductance	0.8/0.8 pu
	Magnetization resistance and inductance	500
Load1	Variable Inductive Load	0.5 – 10MVAR
Load2	Resistive	5MW

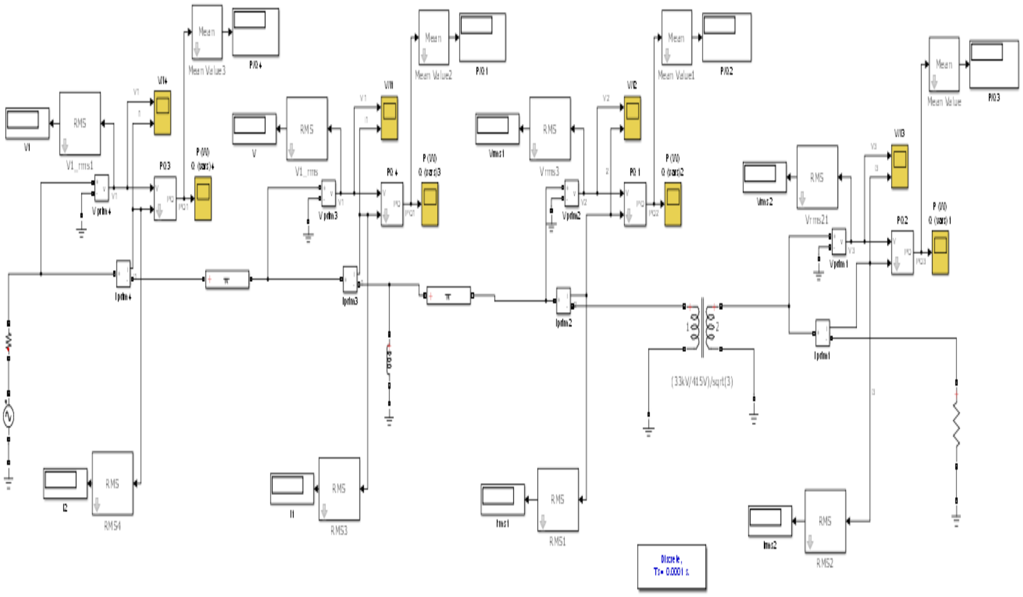

Figure 2: Simulated network

Variable power factor was induced at Bus 2 by varying the inductive load connected therein. When the network was built in Simulink, all network parameters were kept constant except the variable inductive load. For every variation of the load, the major parameters of the network were recorded. Table 3 to Table 6 gives the reading obtained from the simulation.

3.0 Results and discussion

Following the investigations carried out at the substation, the following data were obtained on the respective outgoing feeders from the injection substation and they are as shown Table 3 to Table 6 below.

Table 3: Data Obtained on Feeder1

S/N	P (kW)	Q (kVAR)	Current (A)	Power Factor
1	25390	15810	863.6	0.8489
2	21030	13930	766.7	0.8337
3	17060	11900	667.2	0.8202
4	12300	8877	523.3	0.8109

5	**9821**	**6809**	**431.3**	**0.8218**
6	**8873**	**5815**	**389.3**	**0.8364**
7	**7722**	**4311**	**331.6**	**0.8731**
8	**7148**	**3305**	**298.5**	**0.9077**
9	**6687**	**2283**	**270.8**	**0.9464**
10	**6415**	**1277**	**252.1**	**0.9808**

Table 4: Data Obtained on Feeder 2

S/N	**P (kW)**	**Q (kVAR)**	**Current (A)**	**Power Factor**	**Loss (kW)**
1	**4628**	**15820**	**863.7**	**0.2808**	**20762**
2	**4669**	**13930**	**766.7**	**0.3178**	**16361**
3	**4666**	**11900**	**667.2**	**0.3650**	**12394**
4	**4672**	**8879**	**523.4**	**0.4657**	**7628**
5	**4643**	**6811**	**431.3**	**0.5633**	**5178**
6	**4653**	**5817**	**389.4**	**0.6246**	**4220**
7	**4661**	**4313**	**331.6**	**0.7340**	**3061**
8	**4667**	**3307**	**298.5**	**0.8159**	**2481**
9	**4646**	**2285**	**270.8**	**0.8973**	**2041**
10	**4646**	**1279**	**252.1**	**0.9641**	**1769**

Table 5: Data Obtained on Feeder3

S/N	**P (kW)**	**Q (kVAR)**	**Current (A)**	**Power Factor**	**Loss (kW)**
1	**4292**	**772.4**	**245**	**0.9842**	**336**
2	**4330**	**779.2**	**247**	**0.9842**	**339**
3	**4327**	**778.7**	**246.9**	**0.9842**	**339**
4	**4332**	**779.7**	**247.1**	**0.9842**	**340**
5	**4305**	**774.8**	**246.3**	**0.9842**	**338**
6	**4314**	**776.4**	**246.6**	**0.9842**	**339**
7	**4322**	**777.8**	**246.8**	**0.9842**	**339**
8	**4328**	**778.9**	**247**	**0.9842**	**339**
9	**4308**	**775.2**	**246.4**	**0.9842**	**338**
10	**4308**	**775.4**	**246.4**	**0.9842**	**338**

Table 6: Data Obtained on Feeder 4

S/N	P (kW)	Q (kVAR)	Current (A)	Power Factor
1	4205	0	19140	1.0000
2	4243	0	19220	1.0000
3	4240	0	19220	1.0000
4	4245	0	19230	1.0000
5	4218	0	19170	1.0000
6	4227	0	19190	1.0000
7	4235	0	19210	1.0000
8	4241	0	19220	1.0000
9	4221	0	19170	1.0000
10	4221	0	19180	1.0000

The graph of current at Bus 2 is plotted against the power factor therein and the result is shown in Figure 3.

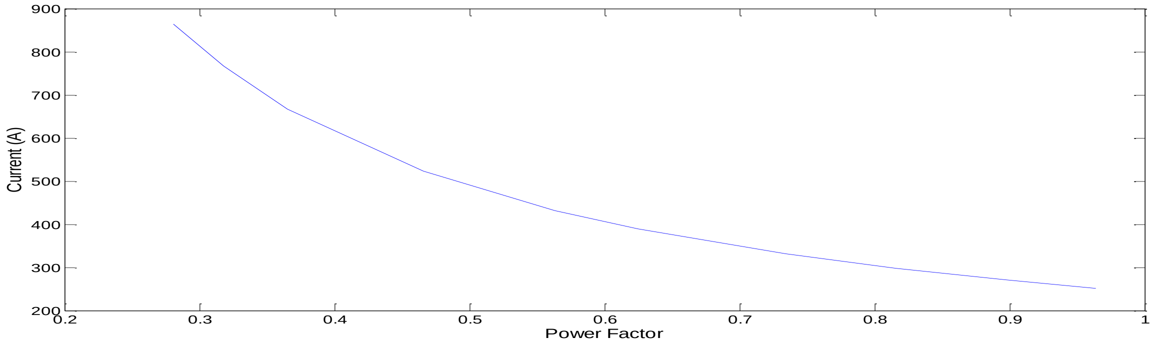

Figure 3: Variation of current against power factor on Feeder 2

It can be seen from the graph that as the power factor decreases, the current that flows through the bus increases. This indicates that the power loss in that section of the network will equally increase with a decrease in the power factor and this leads to increase in cost of electricity bills. Obviously, this was proven in Figure 4 where it is shown that the loss in power increases with decrease in power factor at Bus2. The implication of this finding is that for a given load connected in the network, if the power factor is low, more power than usual will be supplied from the main to power the same load. This is a share waste of power in the network. The result is in line with a study on economic improvement of power factor correction in [13].

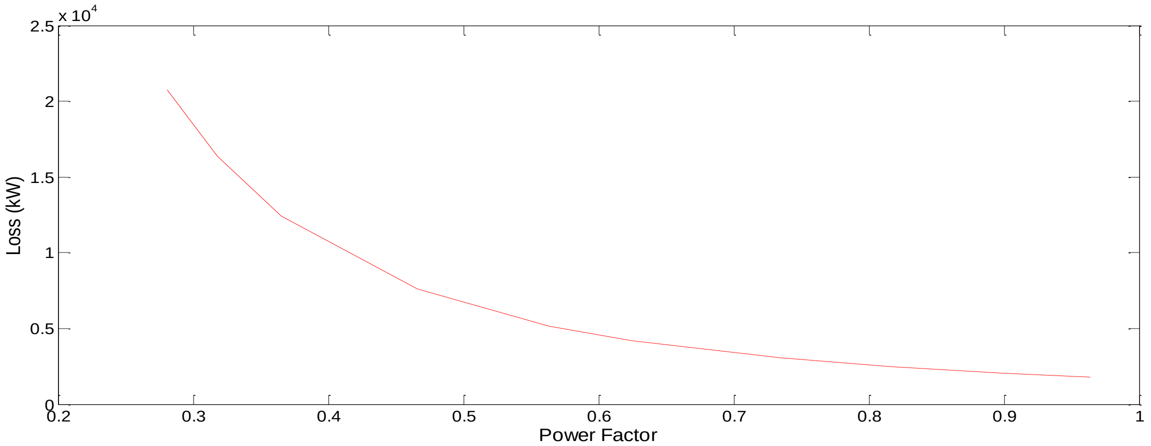

Figure 4: A plot of power loss against power factor on feeder2

The theoretical plot of Eqn. 8 at constant resistance R is a parabola on top of horizontal axis. The plot of power loss against current at Bus 2 is shown in Figure 5. A critical study of the graph shows that its extrapolated form is a parabola that is on top of the horizontal axis. This conforms to the theoretical prediction given by Eqn. 8, indicating that the network is majorly resistive.

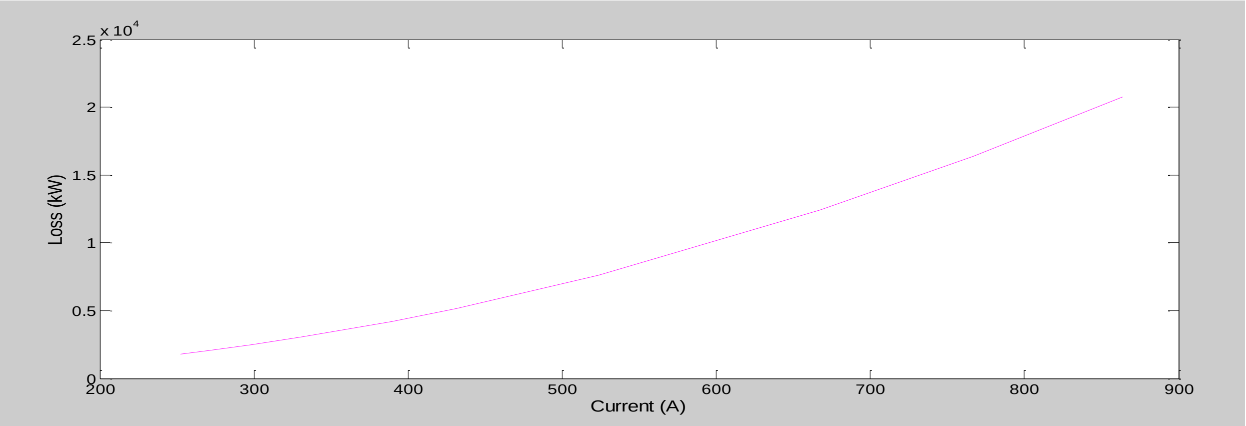

Figure 5: A plot of power loss against current on Feeder 2

3.2 Propagation of power factor variations

This study further investigated the tendency of power factor propagation in the network following a decrease in power factor at any of the Feeders. This is done by changing the power factor at the reference bus and monitoring the power factor values at every other Bus. The graphical representation of this scenario is shown in Figure 6.

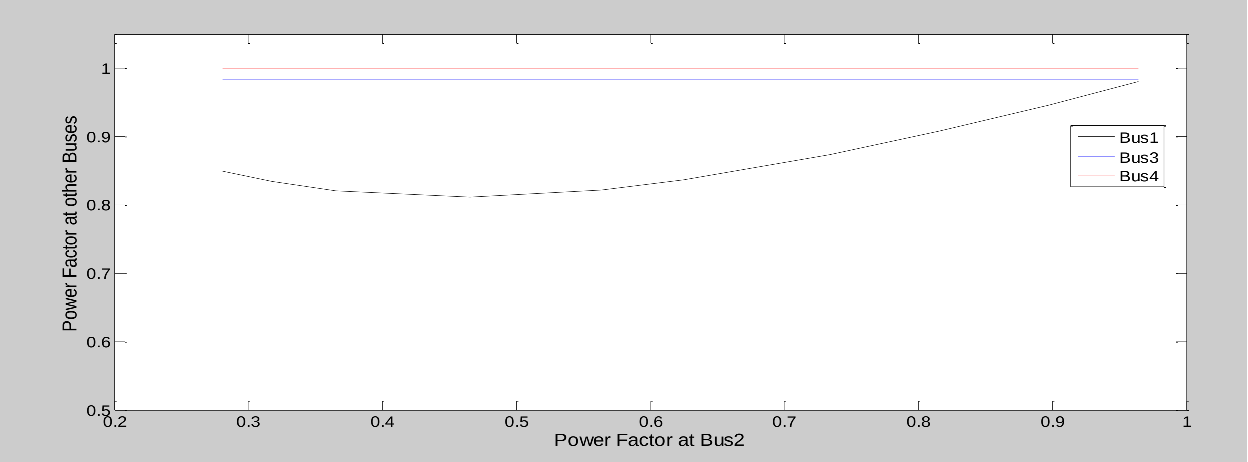

Figure 6: A plot of power factor at other Feeders against the power factor on Feeder 2

It can be seen in Figure 6 that apart from the power factor at Feeder1 that varies slightly with the variations in the power factor at Feeder2, the power factor at the other downstream Bus bars (Feeder3 and Feeder4) are constant. This implies that the variation in power factor at any Bus bar of the network that is probably caused by the load connected therein will not have effect on the power factor recorded at other Bus bars. In other words, power factor variation does not propagate from one point to another in a network. This is evident in a power flow study in [14].

If the preceding deduction is true, it implies that the loss incurred at any reference point in a network will not affect the magnitude of loss incurred at other parts of the network provided power factor variation is the main source of the power loss at the reference point. This assertion is validated by results shown in Figure 7. It is shown in the plot that the power loss at Feeder3 remains constant irrespective of the variation in power loss at Feeder2.

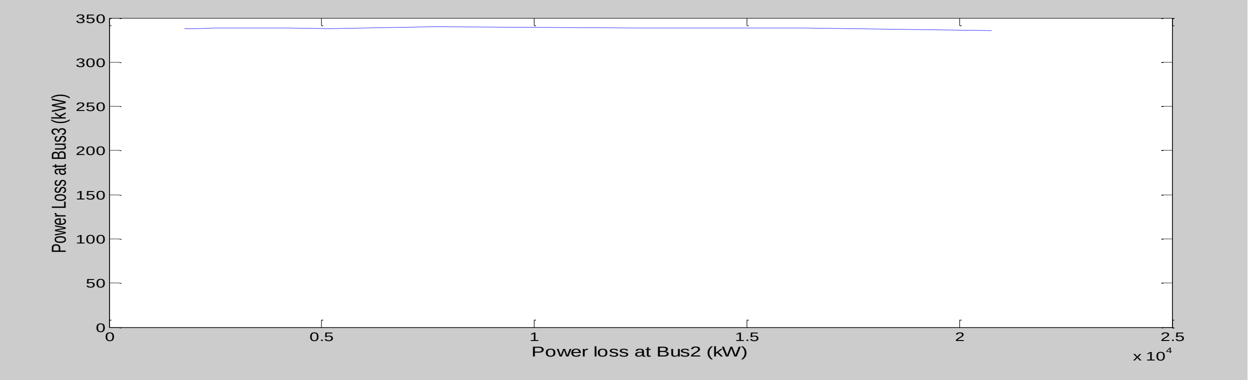

Figure 7: A plot of power loss at Feeder 3 against power loss on Feeder2

3.3 Best placement of capacitor bank for loss reduction

The results of the analysis carried out on the studied network shows that for effective loss reduction, capacitor banks should be installed only at the point(s) where power factor is below normal. Those points are of course the load points where the connected reactive load lowers the power factor. This observation is timely because some power utility companies can erroneously install capacitor bank at a central location in their network hoping that that will help to reduce the power loss due to power factor reductions at load points. Since power factor variations cannot propagate in the network, capacitor banks should be installed at problem locations.

4.0. Conclusion

The research thoroughly studied power loss in a distribution network that is caused majorly by power factor reduction in the network. A section of Nekpenekpen Distribution network in Benin is used as a case study. The selected section of the network is a feeder that supplies two outstanding load clusters; one is inductive while the other is resistive.

It was found in the cause of the research that the major cause of low power factor at a point in a network is the type of load connected at the point. If the load is heavily reactive, the power factor at that point is expected to be lower than normal. However, low power factor was also noted to be one of the major sources of power losses in a network. This is because when the power factor is small, the reactive component of load current is high while the real component of the load current is decreased. But only the real component is used to power a load. This implies that more net load current than normal is required to power a given load in that section of the network.

However, it was established that the higher the current that flows through a branch in a network, the higher the power loss recorded therein. This is because of the ohmic power drop across the resistance of the network element which is directly proportional to the square of the current that passes through the element. Since low power factor results in higher demand of load current, the ohmic power loss in the network will be high at reduced power factor.

One striking discovery made in this research is that if capacitor bank is to be installed in the network to reduce power loss, the optimal point of installation should be at the point where the power factor is small. As shown in this research, low power factor and its associated power loss do not propagate from one part of the network to the other. And such power factor and associated loss reduction do not affect the magnitude of power factor and power loss recorded at other parts of the network. These observations imply that the optimal position for installing compensating capacitor bank in a network for power loss purpose is at the problem area. This observation is very useful for power system engineers who hitherto thought that the installation of capacitor bank at a central point in a network will help to reduce power loss due to low power factor at certain points in the network.

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