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EFFECTS OF LOSSES ON NIGERIA ELECTRIC POWER DISTRIBUTION SYSTEM

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ABSTRACT

The high level of technical and non-technical losses in power distribution systems contribute immensely to the inefficiency of energy supply and poor revenue in the power system. Reducing losses therefore is a necessary objective in the management of any electrical utility. This paper describes the context of losses in power distribution systems and investigates methods of reducing such losses. The power flow solution of the radial network was obtained and the losses computed. The use of capacitor placement to reduce transmission losses was investigated. Results show that high technical losses are as a result of poor management practice.

Keywords: *Energy losses, distribution power flow, distribution loss reduction*

1. INTRODUCTION

The distribution system which is next to the end users of electrical energy is the most neglected of all the components of the electrical system in terms of infrastructural development and quality of staff. This is the section of the power system that deals directly with consumers who are the main reasons for the generation, transmission and distribution of energy. They are the ones to evaluate the reliability and availability of the energy supply. The distribution system equipment is poorly maintained and yet it is expected to deliver the high quality product to consumers. No wonder that the highest component of energy losses come from this level.

In Nigeria today, it is a known fact that the quality of electrical energy supply is poor. Most of the time electricity is not available to consumers and many times when it is available; it cannot be utilized for good works [1], [2]. It is also a known fact that serious efforts are being made to improve the availability of electrical energy to Nigerian consumers. Nigeria has been classified among nations with the highest technical and non-technical losses. It was said that the percentage energy loss in the system is about 33% [3]. This is very alarming and raises the question that if enough energy is available at the generation level, will this energy really be available to consumers and at affordable and competitive price? This is a question that cannot be wished away but must be given serious considerations at this stage of electrical system upgrade in Nigeria.

The goal of the paper is to investigate the sources of technical losses in the distribution system, show that capacitor compensation can effectively minimize low voltage and reduce transmission losses. The Ile-Ife 11kV distribution network is used as case study in this paper. The power flow of the network is obtained using Newton solution technique. The transmission losses are then computed while the transformer losses are estimated. The total technical losses are then computed based on the computed transmission losses and estimated transformer losses. This is then compared with standard losses which are expected to be about 10% of the system generation/load. The use of capacitor compensation was demonstrated by installing capacitor at the most strategic location on the system.

2. SOURCES OF ENERGY LOSSES IN POWER DISTRIBUTION SYSTEMS

The losses in power distribution systems can be classified as technical and non-technical losses. The technical losses are related to energy distribution process while the non-technical losses are related to the customer management process [4].

Technical losses in electrical networks are as a result of the physical nature of the system and cannot be avoided but can be reduced. The causes of technical losses are:

1. Resistances of the conductors used for energy transmission.
2. No-load and copper losses in transformer.
3. Unbalances between phases on low voltage supply networks.

Distribution networks have higher r/x ratio compared with the transmission network and because of the low voltage at which it is operated, they experience high I2R loss. This has effects on the generation capacity requirements and on the quality of the power supply causing possible low voltage at the consumer end. The way to determine the energy loss on line is to determine the difference between the power input into the line and the power output. This is done by the power flow programmes [5].

The transmission line is not the only source of technical loss in the network. Another major source is the transformer. Several transformers are installed in the distribution network. They are usually operated close to their rated value and in many occasions above the rated value.

The transformers installed in electricity supply systems are expected to be extremely efficient when compared with other machines. There are no moving parts, and large modern power station and transmission transformers are designed to operate at very high efficiency. The transformers are estimated to account for about 40% of the total technical losses in the distribution systems. Losses are relatively higher when transformers are lightly or heavily loaded. Most transformers are overloaded in the Nigerian distribution system. This is the reason why load shedding is carried out during the evening peak demand period by the utility. Therefore, losses due to transformers may exceed the 40% estimate in Nigeria.

The practice whereby any size of conductor is used as alternative to feeder-pillar fuses can also increase the technical losses whereby the 'fuse' becomes a dummy load on the system because it fails to rupture when expected.

Non-technical energy loss is the component of the energy that is consumed but could not be accounted for by the utility. This is the difference between the energy supplied and the energy consumed (that is energy paid for) plus technical losses. The sources of non-technical losses include

1. Non-metered energy (consumption losses). This may be due to illegal connections, delay in the installation of meters, tampering with installed meters, faulty meters or faulty connection.
2. Unbilled energy which may be as a result of poor record keeping or incorrect invoicing.
3. Unbilled energy which may be due to unpaid bills (collection losses).

The distribution systems account for the highest percentage of energy losses in power systems. This is obvious because of the proximity of the staff to consumers and because this is where generation of fund takes place. A very high power system loss translates to high tariff and high operating cost. Table 1 shows the classification of losses in relation to the strength of the operating system [4]. The table shows that when the system losses is above 20% of the energy supply, then that system is really in a crisis situation and requires complete restructuring.

3. Power Flow Solution Techniques at the Distribution Level

Considerable research work has been carried out in the development of computer programs for power flow analysis of large power systems. The conventional power flow analysis methods were essentially developed to solve problems at the transmission network level. The distribution system due to its radial nature and low x/r values presents a unique challenge in power flow calculation. These conventional programs can encounter convergence difficulties when applied to radial distribution system with a large number of buses containing lines with high r/x ratio. Therefore, efforts have been made to develop modified versions of these conventional load flow methods to meet the peculiar requirements of the distribution system.

Several algorithms have been proposed in the literature for the solution of the distribution power flow problems [6]-[11]. They may be classified as the modified Newton-Raphson method, the fast decoupled method and the modified Gaussian method. Some of these methods require solving the Newton or Newton-like Jacobian matrix equation while others do not require the computation of the Jacobian matrix. The method used in this paper does not require the computation of the Jacobian matrix. An equivalent system impedance matrix is computed and this is used iteratively to calculate the change in voltages at other nodes relative to the voltage at the source .The method is fast and ensures convergence.

Table 1: Performance indices of Power Systems

Percentage of System Loss (L)	Rating of Organization	Comments
L < 10%	Excellent	Efforts to maintain the level and vigilance
L = 10%	Good	Major investment required if losses are to be reduced further.
10% < L < 15%	Fair Significant commercial losses	Improvement possible in the existing structure.
15% < L < 20%	Improvable organization. Major commercial losses	Partial reorganization sometimes is necessary. Establishing the loss reduction as a strategic project and mobilizing the company
20% < L < 30%	Defective Substantial losses	In depth reorganization. A strategic project is necessary.
L > 30%	Highly deficient organization Exceptional situation linked to a crisis in the power sector.	Reconstructing the company from the ground up,

The static power flow problem involves the calculations of the voltage magnitude and angle at all buses for a given load condition. Once the voltages are calculated, the power flow in each line and transformer can be determined and hence the transmission losses can also be computed.

For an N bus system, the real and reactive power injection at bus i can be expressed as a non-linear function of the voltage magnitudes and angles as shown in eqns. 1 and 2.

$$P_i = P_{gi} - P_{Li} = \sum_{k=1}^{N} V_i V_k Y_{ik} \cos(\theta_{ik} - \alpha_{ik}) \quad (1)$$

$$Q_i = Q_{gi} - Q_{Li} = \sum_{k=1}^{N} V_i V_k Y_{ik} \sin(\theta_{ik} - \alpha_{ik}) \quad (2)$$

$$\text{for } i = 1,2 \ldots\ldots\ldots N$$

Where P_i and Q_i are the real and reactive power injected to bus i, V_i and θ_i are the voltage magnitude and angle respectively of bus i, Y_{ik} is magnitude of the admittance connecting bus i to bus k while α_{ik} is the admittance angle. The power flow problem can therefore be formulated as the solution of a set of nonlinear equations in the form:

$$f(\theta, V) = 0 \quad (3)$$

$$g(\theta, V) = 0 \quad (4)$$

Eqns. (3) and (4) are solved iteratively using the Newton-Raphson's technique. The resulting Newton matrix equation as shown in eqn.(5). The changes in the voltage magnitudes and angles as obtained by solving equation (5) at each iteration.

$$\begin{bmatrix}\Delta f^j \\ \Delta g^j\end{bmatrix} = \begin{bmatrix}\dfrac{\partial f^j}{\partial \theta} & \dfrac{\partial f^j}{\partial V} \\ \dfrac{\partial g^j}{\partial \theta} & \dfrac{\partial g^j}{\partial V}\end{bmatrix}\begin{bmatrix}\Delta \theta \\ \Delta V\end{bmatrix} \quad (5)$$

These variables are updated at the end of each iteration as follow

$$\theta_i^{j+1} = \theta_i^j + \Delta\theta_i^j, \text{ and } V_i^{j+1} = V_i^j + \Delta V_i^j \quad \text{for } i = 1,2,\ldots\ldots\ldots N \quad (6)$$

This is the procedure for the Newton-Raphson solution technique. As stated earlier, this technique may fail to converge when applied to the radial distribution system. The method used in this paper may be summarized as follows.

Let Z_{branch} be a diagonal matrix of the branch impedances, [A] the matrix of the connectivity of the nodes in the network, V_{bus} the array of the bus voltages excluding the source voltage, I_{bus} the bus injection current while Y_{shunt} the bus shunt admittance matrix, the relation between the source voltage and voltages at other buses can be expressed as shown in eqn. 7.

$$[\Delta V] = [Z_{System}]\langle [I_{bus}] + \mathrm{diag}(Y_{shunt})V_{bus}\rangle \quad (7)$$

Where $[Z_{System}] = A^T[Z_{branch}]A$, $\Delta V_i = V_s - V_i$ and V_s is the source voltage. Z_{system} is computed at the beginning of the computation, and eqn. (7) is solved repeatedly until $|V_s - V_i|$ is within acceptable tolerance. This method is fast and converges very fast. Since the lines are short, the shunt admittances of the lines may be neglected. If shunt capacitors are used, then the Y_{shunt} will represent the equivalent admittance of the capacitance.

3. REDUCING TRANSMISSION LOSSES BY CAPACITOR PLACEMENT

High current flow in a line is caused by high voltage drop across the line and the higher the current flow the higher the transmission loss. Therefore, reducing transmission loss may be viewed as reducing the voltage drop along the line. There are a number of methods that can be used to improve system voltages. The system voltage may be improved by placing capacitor at strategic location in the system [15], [16]. This will improve the reactive power distribution in the system. Another method is to reconfigure the network by switching such that the power flow is direct in the direction that ensures the reduction of losses and improve the voltage profile [12] – [14]. The Flexible alternating current transmission system can also be used to improve the performance of the network [2]. The Nigerian distribution networks are radial and have no provisions for switching. The capacitor placement is considered in this paper.

The transmission loss of a line is the product of the line resistance and the square of the current flow in the line

$$P_{Loss-ij} = I_{ij}^2 R_{ij} = \left((I_{ij}^r)^2 + (I_{ij}^{im})^2\right)R_{ij} \quad (8a)$$

$$P_{Loss-ij} = \left(\frac{V_i^2 + V_j^2 - 2V_iV_jG_{ij}\cos\theta_{ij}}{Z_{ij}^2}\right)R_{ij} \quad (8b)$$

The total system loss is

$$P_{Loss} = \sum_{l=1}^{NL} I_l^2 R_l = \sum_{l=1}^{NL}\left(\frac{V_i^2 + V_j^2 - 2V_iV_jG_{ij}\cos\theta_{ij}}{Z_{ij}^2}\right)R_{ij} \quad (9)$$

The current in the branches can be reduced by placing capacitor at strategic location in the network. Let a capacitor which draws a reactive current I_C from the system be connected to bus m in the radial system. Assuming that the bus voltages are the same before and after the connection of the capacitors, the current in all the branches which can be traced from node m to the source will increase by approximately I_C. The new power loss in line l will now become

$$P_{loss-l} = I_{new\_l}^2 R_l = \begin{pmatrix}(I_l^{re})^2 + (I_l^{im})^2 \\ -I_C(2I_l^{im} - I_C)\end{pmatrix}R_l \quad (10)$$

The power loss in this line is reduced by a quantity given by eqn (11).

$$P_{Loss\_ij(reduction)} = I_C(2I_{ij}^{im} - I_C)R_{ij} \quad (11)$$

If k is the number of lines between bus m and the source, then conservatively, the total system loss reduction by placing capacitor at bus m is

$$P_{Loss(reduction)} = \sum_{L=1}^{k} I_C(2I_L^{im} - I_C)R_L \quad (12)$$

The maximum current that will lead to maximum reduction is obtained by differentiating equation (12) with respect to I_C. The I_{Cmax} is

$$I_{Cmax} = \frac{\sum_{L=1}^{k} I_L^{im} R_L}{\sum_{L=1}^{k} R_L} \quad (13)$$

and the reactive power injection is

$$Q_{injection} = X_C I_C^2 = \frac{I_C^2}{\omega C} \quad (14)$$

Most times it will be necessary to inject reactive power at more than one bus so optimal placement analysis will be required.

4. APPLICATION TO ILE-IFE DISTRIBUTION NETWORK

The system considered is the Ile-Ife 11-kV distribution system. The source supplies for different distribution system. Since the voltage at the source is assumed to be regulated, the loading on each of the feeders will not affect the other feeders, hence one of the feeders is considered in this paper. This feeder consists of twenty seven buses and twenty six lines and transformers. The transformer ratings vary from 250kVA to 500kVA. The no load data for these transformers were not available hence it was not possible to determine the transformer no load losses. The line parameters were obtained and properly modeled using the pi equivalent. The distance between the source and the last load point on the system is about 10km. Figure 1 shows the one line diagram of the feeder while the line and bus data of the system are given in the appendix. The total load demand of this feeder is about 5.9MW which is high for a single feeder.

Equation 7 was used to solve the power flow problem. Table 2 shows the summary of the solution. The system experiences low voltage at various transformer stations at the peak load as can be observed on column 2 of Table 2. Also the power loss is very high at 31.7%. This is unacceptable compared with the expected loss of less that 10%. From Table 1 above, the system falls into the category defined as "Highly deficient organization Exceptional situation linked to a crisis in the power sector" and the recommended remedy is to "Reconstruct the company from the ground up". The solution presently employed is to shed loads on various transformers to reduce the total load.

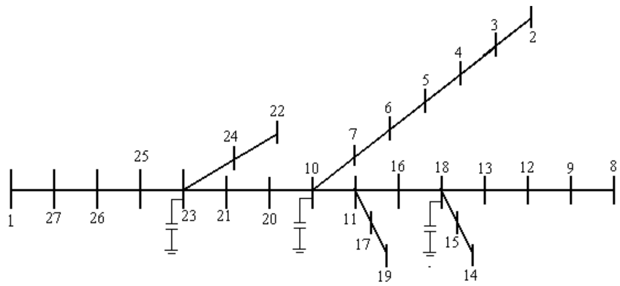

Figure 1: Single line diagram of Parakin Ile-Ife system

The option of shunt capacitor on the system was considered and columns three and four show the improvement when capacitor were placed at a number of transformer substations. There were slight improvements in the voltage profile while the system loss reduced to 22.3%. This is still very high and since the capacitor placement was close to the optimum, this type of correction cannot totally solve the problem. There is need to reconstruct the system.

This is the feeder that is more heavily loaded and experiences low voltage out of the four feeders in Ile-Ife. The losses on other feeders range from 2.5% to 8.5%. The Parakin feeder accounts for about 31% of the total load and 80% of the transmission losses.

Table 2: Voltage profile of the Ile-Ife distribution system.

Bus number	Base case Voltage	Voltage with capacitors at buses 10 & 18	Voltage with capacitors at buses 5,10,18 & 23
1	1.0500	1.0500	1.0500
2	0.8295	0.8418	0.8522
3	0.8313	0.8437	0.8539
4	0.8326	0.8449	0.8550
5	0.8358	0.8481	0.8580
6	0.8377	0.8499	0.8596
7	0.8406	0.8529	0.8623
8	0.7916	0.8065	0.8159
9	0.7942	0.8090	0.8184
10	0.8488	0.8609	0.8697
11	0.8426	0.8550	0.8638
12	0.7972	0.8120	0.8213
13	0.8069	0.8215	0.8307
14	0.8036	0.8183	0.8275
15	0.8050	0.8196	0.8288
16	0.8335	0.8464	0.8554
17	0.8406	0.8530	0.8619
18	0.8077	0.8223	0.8315
19	0.8410	0.8534	0.8623
20	0.8662	0.8773	0.8854
21	0.9262	0.9337	0.9396
22	0.9452	0.9516	0.9567
23	0.9463	0.9526	0.9577
24	0.9454	0.9517	0.9568
25	0.9646	0.9698	0.9740
26	0.9835	0.9875	0.9908
27	1.0162	1.0182	1.0199
Total Gen	7754.2	7408.6	7199.5
(Kw)	5886.8	5886.8	5886.8
Total Load	1867.4	1521.8	1312.7
(Kw)	31.7 %	25.9%	22.3%
Loss (Kw)			
%STage Loss			

The observation on this feeder is applicable to many distribution networks in the Nigeria system. The implication of this is that even with sufficient and reliable generation and transmission systems, the distribution will still pose a serious problem to availability of electricity supply in Nigeria. The cost to consumers will also be high since the consumers are expected to pay for these losses.

5. CONCLUSION

This paper has considered the problem of technical losses in the power distribution system. A simple technique for solving the radial power flow problem was presented. The power flow of the network was computed and the transmission losses calculated. It was shown that at the 11kV level, the transmission loss increases as a square of the line current. Since the line current is a function of the system load, as the load demand increases, the transmission line also increases. It was shown that the Nigerian distribution networks are susceptible to overloads which may result in unacceptable transmission losses.

The low voltages experienced on the 11-kV lines are transferred to the low voltage sides of the transformers and the consumers experience low voltage also. The only solution employed currently is load shedding.

The main causes of non-technical losses are outlined. It is clear that reducing the non-technical losses require paying better attention to distribution section of the network. The equipment at this level should be upgraded; the quality of the staff should be improved. Data collection should be given priority.

Finally, it should be noted that no matter the investment to upgrade the transmission and distribution systems, if equal amount of attention is not placed on the upgrade of the distribution system no significant achievement should be expected.

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Appendix: Bus and Line data of the11-kV Ile-Ife distribution network

S/N	P (kVA)	Q (kVAr)	Bus Fro	Bus To	R (p.u)	X (p.u)
1	0.0	0.0	2	3	0.04132	0.00754
2	333.7	250.3	3	4	0.02479	0.00452
3	38.3	28.8	4	5	0.02893	0.00528
4	424.9	318.7	5	6	0.01240	0.00226
5	316.0	237.0	6	7	0.01653	0.00302
6	212.2	159.1	7	10	0.03719	0.00679
7	288.7	216.5	10	11	0.01653	0.00302
8	330.6	248.0	10	20	0.02893	0.00528
9	171.2	128.4	11	19	0.02479	0.00452
10	0.0	0.0	11	16	0.02893	0.00528
11	0.0	0.0	19	17	0.02066	0.00377
12	281.6	211.2	16	18	0.09917	0.01810
13	518.5	388.9	18	15	0.03719	0.00679
14	209.9	157.4	15	14	0.04545	0.00830
15	309.4	232.0	18	13	0.00413	0.00075
16	387.2	290.4	13	12	0.08678	0.01584
17	151.8	113.9	12	9	0.04132	0.00754
18	0.0	0.0	9	8	0.05372	0.00980
19	321.1	240.8	20	21	0.09091	0.01659
20	394.5	295.9	21	23	0.02893	0.00528
21	247.8	185.9	23	24	0.02066	0.00377
22	292.5	219.4	23	25	0.02479	0.00452
23	0.0	0.0	24	22	0.00413	0.00075
24	58.8	44.1	25	26	0.02479	0.00452
25	148.8	111.6	26	27	0.04132	0.00754
26	238.3	178.7	27	1	0.04132	0.00754
27	211.0	158.3				