LAUTECH Journal of Engineering and Technology 7(1) 2012: 101-108

OPTIMAL CAPACITOR PLACEMENT FOR POWER LOSS REDUCTION ON DISTRIBUTION SYSTEMS

Adejumobi I.A[1,a] and Opeodu F.A[2,b]

[1,2]Department of Electrical and Electronics Engineering,
University of Agriculture, Abeokuta, Nigeria
[a]engradejumobi@yahoo.com
[b]opefranc@yahoo.com

ABSTRACT

Electrical and Electronic equipments are designed to operate on specified voltage and frequency. This objective may not be realized when there is supply-demand power imbalance, with heavy power loss on the distribution system being one of the identified major causes. Power distribution system in Nigeria is characterized high power loss which consequently leads to poor quality of electric power reaching consumers. One of the identified problems has been the abnormal excessive loadings on the distribution feeders. The paper considered a novel approach to minimize power loss on the radial distribution systems. The work considered maximum loadings on each node of the distribution feeders when estimating power loss.. Further reduction in power loss was expected when optimal size and location of the shunt capacitor were determined on the considered feeder nodes. carried out on feeder nodes. From the derived basic power equations, an algorithms coded with Visual Basic Net was developed to provide simple and flexible task in determining optimal capacitor sizing and its placement on the distribution feeder that would achieve minimum power loss. The power loss before and after placing shunt capacitor optimally were determined for each feeder. Using the electric power distribution system of Ilorin, three of the distribution feeders were used as a case study, to estimate the power losses, by considering 50mm^2, 80mm^2, 100mm^2 and 150mm^2 ASCR cables. Using the developed algorithm, the appropriate node location for shunt capacitors to further reduce power loss was done. The results from the analysis showed that the considerable amount of energy can be saved by electricity utilities when the adoption of the shunt capacitor is considered on the primary distribution.

Key Words: Distribution system, power loss, optimal Shunt capacitors, algorithms, primary feeders, economy.

Introduction

The poor and inefficient supply of electric power in Nigeria for domestic, commercial and industrial uses had been the major concern of the Nigeria populace. Commercial activities are folding up, and some of Nigeria industrial merchants have been sent packing their wares from the soil of Nigeria to neighborhood West Africa countries with more reliable electricity supply systems. Electricity generation capacities in Nigeria are low and the available ones are not efficiently and effectively distributed.

One of the identified factors for the ineffectiveness in our energy supply system in Nigeria is the very high power loss being experienced in the power distribution sector; the major link between electricity supply authority and consumers of the electric power. A distribution system is the one from which the power is distributed to various users through distribution feeders. Feeders are conductors of large current carrying capacity, carrying the current in bulk to the feeding nodes. Distribution losses account for the bulk of power system losses (Pabla, 2000). More so, the capital investment for distribution networks is a considerable fraction of total capital investment on power system. Hence, magnitude of the distribution system active power losses needs to be controlled if the overall economics of the utilities must be profitably kept and the consumers of electricity efficiently fed. Therefore, the need to determine appropriate conductor sizing and the location of shunt capacitor on distribution nodes that would give optimum power transfer to the consumers is a welcome task.

Factors Responsible for Power Losses in the Distribution System: Losses in distribution system are caused among others by (Pabla, 2000).

- Uneven distribution of loads among various feeders and substations
- Inadequate layout of feeders
- Overloading of distribution transformers.
- Poor power factor due to inadequate reactive compensation
- Uneconomic conductor size

Conductor Selection for Distribution System: There are four major types of overhead conductors used for electric energy distribution.

- AAC - All Aluminium Conductors.
- AAAC - All Aluminium Alloy Conductors.
- ACSR - Aluminium Conductor Steel Reinforced
- ACAR - Aluminium Conductor Aluminium-Alloy Reinforced.

The selection of the optimum conductor type and size for a given distribution line design requires a complete understanding of the characteristics of all the available conductor types. This understanding must encompass more than just the current carrying capability or thermal performance of a conductor. It must include a systematic approach to conductor selection: line stability versus current loading; economic operation versus thermal loading: conductor creep and resultant sag under high temperature and adverse mechanical loading; metal stress-strain performance and metal fatigue characteristics are just a few of the system design parameters to be evaluated (Ponnavaiko, and Rao, 1982).

Optimal conductor selection is also an important factor contributing to the reduction of power losses in distribution systems.

.

The available conductor sizes used for distribution systems connections in Nigeria are shown in Table 1 (Pabla, 2000).

Table1: The conductor specification used in Nigeria.

ASCR conductor Area (mm^2)	Resistance (Ohm/km)	Reactance (Ohm/km)	Max Current (Ampere)
20	1.394	0.3915	107
30	0.9289	0.382	139
50	0.5524	0.372	193
80	0.3712	0.36	250
100	0.2792	0.353	300
150	0.1871	0.349	398
200	0.139	0.344	482

The importance of shunt capacitor on distribution systems: The capacitor is a source of reactive power. Applying shunt capacitors to primary distribution feeders will provide an alternate source of reactive power that will reduce the level of reactive power provided by the supply system, and the maximum kVA demand. Overall effects are to improve voltage profile on the feeders, and reduce feeder losses and payments for the electric energy consumption. Series capacitors are also applied to distribution systems to reduce losses and improve power factor, but this has a disadvantage of voltage drop across them as compared to shunt capacitors

The appropriate location of capacitors on the feeders will reduce the system current and raise the system voltage, with the following benefits: (Cook, 1964)

- Reduction of loading on thermally limited equipment.
- Reduction of system voltage drop
- Reduction of system losses.
- Improvement of stability.

System Modeling

Power flow analysis is an important basic tool for the technical analyzes of power systems (Glover and Sarma, 1994 and Saadat, 2006). These analyzes are represented in several software applications that facilitate efficient and fast determination of voltage profiles, power losses and overall system performance. Distribution feeders can be radial or loop. For the purpose of this analysis radial lines were considered (Pabla, 2000). Figure1 is a representation of radial distribution feeder with laterals or branch offs.

The root node is the node connected to the substation in the radial distribution network. Main line is the line emanating from the root node. Lateral line is the line emanating from the main line. Sub-lateral line is the line emanating from the lateral line. Minor line is the line emanating from the sub-lateral line.

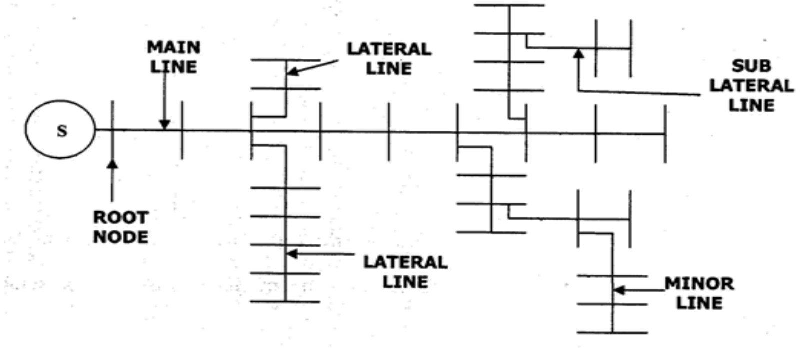

Figure 1: Typical Diagram of a Radial Distribution Network

Power Loss Determination: In order to calculate the power loss on the distribution line, it is assumed that the three-phase radial networks are balanced and can be represented by their equivalent single-line diagram (Saadat, 2006). Constant load are assumed on the system. The distribution transformer losses resulting from electron collision, ionization, and heating are also assumed to be negligible, and is thus neglected. The single- line diagram and the components of the modeling is shown in figure 2.

V_j is the nodal voltage, I_i is the branch current, and I_j is the load current in node j,

Applying current analysis, we have equation (1) (Cook, 1961):

$$I_i = I_{i+1} + I_{j+1} \quad (1)$$

where;

I_i is the current in branch I in amperes

I_{i+1} is the current in branch i+1 in amperes

I_{j+1} is the nodal injection current in node j+1 in amperes.

Assume initial voltage of 1 P.U. at all nodes on feeder and lateral

V_j = 1p.u. for j=1,..,n where n is the total no. of nodes on feeder and lateral.

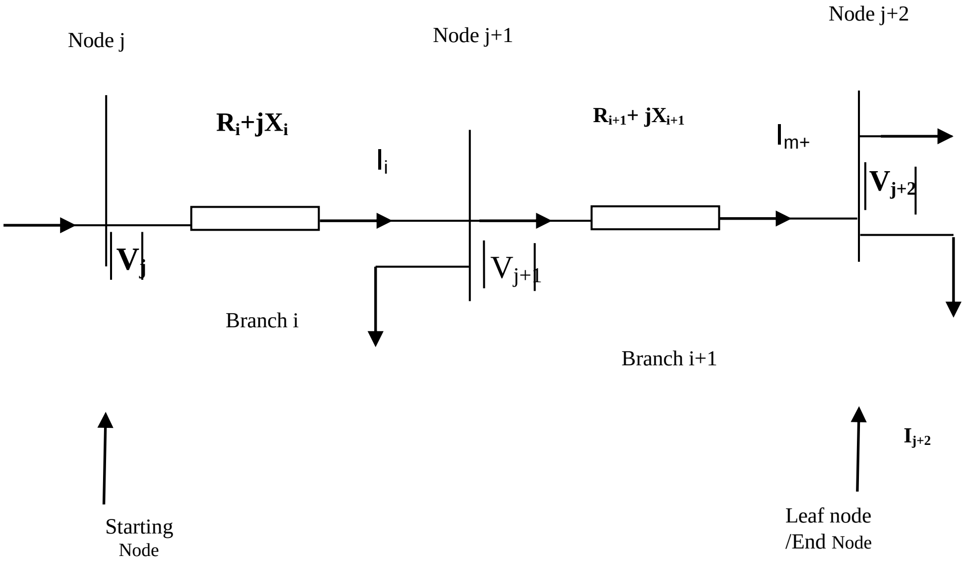

Figure 2: Representative components of the model

Starting from the root and moving towards the feeder and laterals, the nodal current injection at the Kth iteration is given in equation (2) as (Saadat,2006 and Cook, 1961):

$$I_j^k = \frac{S_j^*}{V_j^{k-1}} \quad (2)$$

where;

I_j^k is the nodal current injection at the K^{th} iteration in Amps.
S_j is the load power at node j in MVA.
V_j^{k-1} is the node voltage at the j^{th} node at k-1th iteration in KV.
The load power at node j is given by equation (3) as :

$$S_j = P_j + jQ_j \quad (3)$$

where
$P_j = S_j \mathrm{Cos}\theta$ is the active load power at node j in MW
$Q_j = S_j \mathrm{Sin}\theta$ is the reactive load power at node j in MVAR
$\mathrm{Cos}\theta = 0.7$ is the assumed power factor for the distribution system (Pabla, 2000)
The voltage at node j is given in equation (4) as (Cook, 1961)

$$V_{j+1}^{k-1} = V_j^k - Z_i I_i^k \quad (4)$$

where
V_{j+1}^{k-1} is the present voltage value of bus j at k-1^{th} iteration in KV
V_j^k is the past voltage value of bus j at K^{th} iteration in KV
$Z_i = R_i + jX_i$ is the impedance of branch i in (ohms/km/phase)
I_i^k is the current in branch i at K^{th} iteration in Amps.
The voltage mismatch is computed and compared with a termination criterion shown in equation (5) i.e., (Cook, 1961)

$$\Delta V_j^k = V_j^{k+1} - V_j^k \leq \varepsilon \quad (5)$$

If the criterion is met, then convergence is achieved and the voltage at all the nodes and current in all the branches is obtained.
The total active power loss of the distribution system is given in equation (6) as (Basal, 2009):

$$P_{Lt} = \sum_{i=1}^{n} I_i^2 R_i \quad (6)$$

where;
P_{Lt} is the total active power loss in MW
I_i is the magnitude of current in branch j in amps.
R_i is the resistance of branch I in (Ohms/km/phase).
And the total reactive power loss of the distribution, shown in equation (7) as (Basal, 2009):

$$Q_{Lt} = \sum_{i=1}^{n} I_i^2 X_i \quad (7)$$

where;
Q_{Lt} is the total reactive power loss in MVAR
I_i is the magnitude of current in branch j in amps.
The total reactive power loss of the distribution
Hence, the total power loss is given in equation (8) as :

$$S = \sqrt{P_{Lt}^2 + Q_{Lt}^2} \text{ in MVA} \quad (8)$$

Capacitor Placement For Loss Reduction: The active power loss in a distribution system having n number of branches is given by equation (9) (Cook, 1961)

$$P_{Lt} = \sum_{i=1}^{n} (I_{ai}^2 + I_{ri}^2) R_i \quad (9)$$

where;
P_{Lt} is the total active power loss in the system in MW
I_{ai} is the real component of current in branch i in Amps
I_{ri} is the reactive component of current in branch i in Amps
R_i is the resistance of branch i in (ohm/km/phase)
The total reactive power loss in a distribution system having n number of branches is given in equation (10) as (Glover, and Sarma, 1994):

$$Q_{Lt} = \sum_{i=1}^{n} (I_{ai}^2 + I_{ri}^2) X_i \quad (10)$$

where
Q_{Lt} is the total reactive power loss in the system in MVAR
I_{ai} is the real component of current in branch i in Amps
I_{ri} is the reactive component of current in branch i in Amps
X_i is the reactance of branch i in (ohms/km/phase)
The branch current can be obtained from the power flow solution. The branch current has two components; active (I_a) and reactive (I_r).
The active power loss associated with the active and reactive components of branch currents can be written as in (11) as (Basal, 2009):

$$P_{Lr} = \sum_{i=1}^{n} I_{ri}^2 R_i \quad (11)$$

where
R_i is the resistance of branch i in Ohm/km/phase
P_{Lr} is the active power loss due to reactive component of branch current
I_{ri} is the reactive component of current in branch i
The reactive power loss associated with the active and reactive components of branch currents is written in (12) as (Basal, 2009):

$$Q_{Lr} = \sum_{i=1}^{n} I_{ri}^2 X_i \quad (12)$$

where
X_i is the reactance of branch i in Ohms/km/phase
Q_{Lr} is the reactive power loss due to reactive component of branch current in Amps
I_{ri} is the reactive component of current in branch i in Amps
By reducing the inductive reactive portion of the line loading, the reactive power losses would reduce. With a highly inductive load we reduce the level of inductive load current. This is done by the addition of shunt capacitors.

Placement of Shunt capacitor to reduce loss: The first thing to do is to identify a sequence of nodes to be compensated on the distribution system. This sequence is determined by repetitive applications of loss minimization technique by a single located capacitor. Once the sequence of nodes to be compensated is identified, the corresponding optimal capacitor size at the compensated nodes can be determined. For the purpose of the analysis, we can consider the line diagram in figure 3 (Basal, 2009 and Grainge and Lee, 1981). Let a capacitor C be placed at bus j, and α be a set of branches connected between the source and capacitor buses

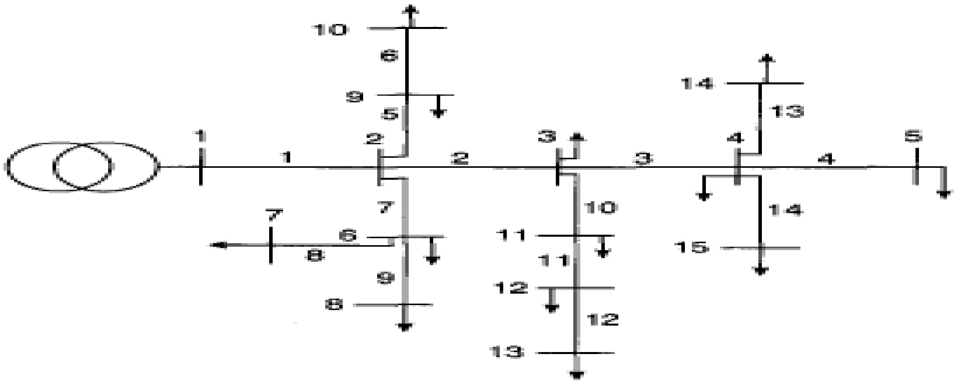

Figure 3: Single Line Diagram of a Distribution System with laterals or branches.

The capacitor will draws reactive current I_c which will change only the reactive component of current of branch set α, leaving the current of other branches not in α unaffected by the capacitor. The active power loss P_{Lr}^{com} associated with the reactive component of branch currents in the compensated system (when the capacitor is connected) can then be written as equation (13) (Basal, 2009)

$$P_{Lr}^{com} = \sum_{i=1}^{n}(I_{ri} + D_i I_c)^2 R_i \qquad (13)$$

where,

P_{Lr}^{com} is the compensated active power loss due to reactive component of current in MW

$D_i = 1$; if branch $I \in \propto$

$= 0$; otherwise

I_c is the current drawn by the capacitor in Amps

I_{ri} is the reactive current of the ith branch in the original system in Amps

The reactive power loss Q_{Lr}^{com} associated with the reactive component of branch currents in the compensated system (when the capacitor is connected) can be written as (14) (Basal,2009):

$$Q_{Lr}^{com} = \sum_{i=1}^{n}(I_{ri} + D_i I_c)^2 X_i \qquad (14)$$

where,

Q_{Lr}^{com} is the compensated reactive power loss due to reactive component of current in MVAR

$D_i = 1$; if branch $I \in \propto$

$= 0$; otherwise

I_c is the current drawn by the capacitor in Amps

I_{ri} is the reactive current of the ith branch in the original system in Amps

The active power loss saving S_a is the difference between eqns.11 and13 and is given by (15) as:

$$S_a = P_{Lr} - P_{Lr}^{com} \qquad (15)$$

where;

P_{Lr} is the initial active power loss due to reactive branch current in MW

P_{Lr}^{com} is the compensated active power loss due to reactive branch current in MW

Resulting to produce (16) (Ponnavaiko and Rao, 1982).

$$S_a = -\sum_{i=1}^{n}(2D_i I_{ri} I_c + D_i I_c^2) R_i \qquad (16)$$

The reactive power loss saving S_r is the difference between eqns. 12 and 14 is given by the equation (17) i.e.

$$S_r = Q_{Lr} - Q_{Lr}^{com} \qquad (17)$$

where;

Q_{Lr} is the initial reactive power loss due to reactive branch current in MVAR

Q_{Lr}^{com} is the compensated reactive power loss due to reactive branch current in MVAR

Resulting to (18) (Basal,2009):

$$S_r = -\sum_{i=1}^{n}(2D_i I_{ri} \qquad (18)$$

The capacitor current Ic that provides the maximum active power loss saving can be obtained from (19) as:

$$\frac{\partial S}{\partial I_c} = -2\sum_{1}^{n}(D_i I_{ri} + D_i I_c) R_i = 0 \qquad (19)$$

Thus the capacitor current for the maximum active power loss saving is equation (20).

$$I_c = \frac{\sum_{i=1}^{n} D_i I_{ri} R_i}{\sum_{i=1}^{n} D_i R_i} \qquad (20)$$

where,

$D_i = 1$; if branch $I \in \propto$

$= 0$; otherwise

I_c is the current drawn by the capacitor in Amps

I_{ri} is the reactive current of the ith branch in the original system in Amps

The corresponding value and the size of capacitor is given in equation (21) and (22) (Basal, 2009)

$$C=\frac{10^6 I_c}{2\pi f V_m} \quad (21)$$

$$Q_c = V_m I_c \quad (22)$$

where;

Q_c is the capacitor size in MVar

V_m is the voltage magnitude of the capacitor bus j in kV

I_c is the current drawn by the capacitor in Amps.

The above process is repeated for all the buses until the highest possible saving for a singly located capacitor is achieved

Software Development utilities and Programming language

The software used to implement the work is Visual Studios, and the programming language used is Visual Basic.Net. It is an object oriented programming language. The language is selected basically because of the ease to achieve a rapid application development with the Microsoft Visual Studio Integrated Development Environment. It is flexible and easy to learn, use and understand; and very fast to code with. The flow chart for the algorithm for power flow analysis and capacitor placement at feeder nodes is shown in figures 4.

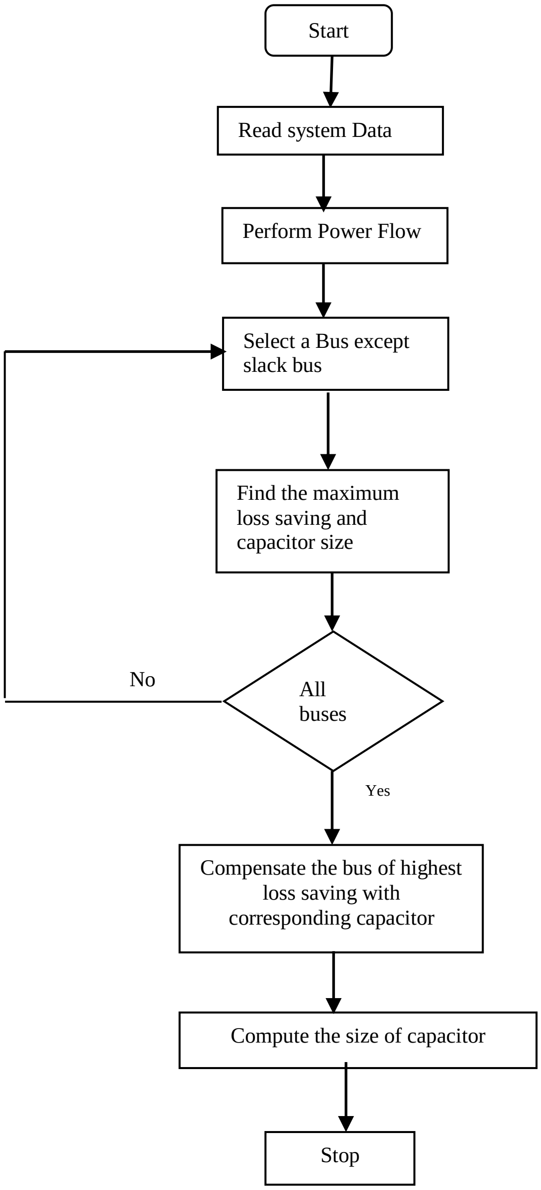

Figure 4: Flow Chart for capacitor placement algorithm

Algorithm for Optimal Conductor Selection

Step 1:Read the number of lateral(s) (L)
Step 2:Read the number of branches in feeder and laterals
Step 3:Read the total number of nodes N(k) of feeder and lateral(s) for k = 1,2,…,T
Step 4: Total number of nodes $N = \sum_{k=1}^{T} N(k)$
Step 5: Read load demand (in MVA) at each node. That is S_j for j =1, 2, 3... N.
Step 6: Initialize real and reactive power loss. $P_{Loss}(i) = 0.0$ and $Q_{Loss}(i) = 0.0$.
Step 7: Read the branches of feeder and lateral(s). That is, i= 1, 2, 3… (N-1).
Step 8: Read resistance and reactance per kilometer for each area of the ASCR conductors. i.e. R and X.
Step 9: Read the length of each braches in kilometer. That is, L_i for i = 1, 2, 3… (N-1).
Step 10: Resistance of each branch $R_i = R \times L_i$ and reactance of each Branch $X_i = X \times L_i$.
Step 11: Read the total number of iteration (ITMAX), for convergence factor ε (0.0001)
Step 12: Set $P_{Lj}(1) = P_{Lj}$ and $Q_{Lj}(1) = Q_{Lj}$ for j = 2,3,..,N.
Step 13: Set $V_j = 11.0 + j0.0$ for j =1,2,…,N and set $V_j(1) = V_j$ for j =1,2,…,N.
Step 14: Find the common nodes of each lateral and the feeder, that is and the branch of feeder corresponding to the node for k = 2, . . .,T.
Step 15: Read the nodes on each lateral.
Step 16: Calculate the current injected into node j, I_j, on main feeder and each lateral for j =2,…,T. using (3.2).
Step 17: Calculate branch current in each feeder and lateral using equation (3.1).
Step 18: Set IT = 1.
Step 19: Set $I_i = I_i(1)$ for i = 1, 2, 3, …, N−1.
Step 20: Compute voltage $|V_j|$ using (3.4) for j = N−1.
Step 21: Compute $|\Delta V_i| = |V_j(1)| - |V_j|$ for j = 1, 2,3,..,N−1.
Step 22: Set $|V_j(1)| = |V_j|$ for j = 1, 2, 3, …, N−1.
Step 23: Compute $P_{Loss}(i)$ and $Q_{Loss}(i)$ for all i = 1, 2, 3, …, N−1 using (3.6)and (3.7) respectively.
Step 24: Find ΔVmax from $|\Delta V_j|$.
Step 25: If $\Delta V\text{max} \leq 0.0001$ go to Step 29 else go to Step 27.
Step 26: IT = IT + 1
Step 27: If IT ≤ ITMAX go to Step 16 else write "NOT CONVERGED" and go to Step 29
Step 28: Write "SOLUTION HAS CONVERGED" and display the results: Real and Reactive Power Losses on each branch, Voltages of each node and total real and reactive power loss for each area of ASCR conductor.

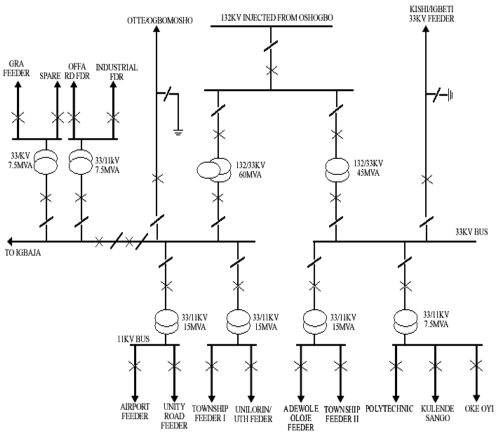

Figure 6: Ilorin distribution Network

Step 29: Stop

Algorithm for optimal capacitor placement

Step 1: Run the optimal conductor selection program and obtain the branch currents.
Step 2: Select a bus and find the maximum loss saving and the corresponding capacitor size from eqns. 18 and 21 respectively. Repeat this step for all nodes in the system, except the source node. Identify the node that provides the highest loss saving.
Step 3: Compensate the node to get the highest loss saving with the corresponding capacitor found from eqn. 21.

Results and Discussion

The data used as test case to test run the programmed algorithm is Ilorin power Distribution system (Adejumobi, 2003). In order to ascertain the usefulness and the authentication of the adopted techniques, only three long and loaded feeders were considered. Applying equations 1 to 21, the developed program was used to calculate the power losses with varying conductor sizes and when capacitors were placed at nodes as shown in Table 2. From the table it is noted that there were appreciable reductions in the power losses on the selected feeder with the inclusion of shunt capacitor optimally,

Table 2: Distribution feeders losses with the conductor sizing and capacitor placements

(ASCR)	Name of Feeder	No of Substations	Power loss before Capacitor Placement (MVA)	Power loss after Capacitor Placement (MVA)	Capacitor Size (Mvar)	Optimal Capacitor Placement Node
Area 50mm^2	Adewole	33	1.955	1.11	2.344	16
	Township Feeder I	29	1.633	0.892	3.362	13
	Township Feeder II	22	1.011	0.557	3.154	9
Area 80mm^2	Adewole	33	1.559	0.876	2.453	16
	Township Feeder I	29	1.299	0.707	3.600	13
	Township Feeder II	22	0.795	0.436	3.306	9
Area 100mm^2	Adewole Township Feeder I	33	1.375	0.77	2.674	16
	Township Feeder II	29	1.144	0.622	3.708	13
		22	0.696	0.381	3.375	9
Area 150mm^2	Adewole	33	1.224	0.684	2.757	16
	Township Feeder I	29	1.0168	0.553	3.798	13
	Township Feeder II	22	0.616	0.336	3.431	9

Conclusion

Out of about seven feeders in the Ilorin distribution system, three long and loaded feeders have been used as test sample for the analysis. Results show that power loss on a feeder reduces with larger diameter conductor size. But appreciated power loss reductions were noted when shunt capacitors were optimally placed on each feeder. Which indicate that substantial savings are achieved when an optimum size shunt capacitors are placed appropriately in nodes of the selected feeders. The technique has not been given keen attention in the distribution systems because of the economics, but it is a useful tool to achieve quality and reliable electric power that would be transferred to consumers.

References

Adejumobi, I. A. (2003): Distribution System Load Growth Prediction: Least Square Regression Approach. Nigerian Journal of Pure and Applied Science**.** 18; 1506 – 1515.

Basal, P.K. (2009).Maximum Loss Reduction by Placement of Capacitor on Radial Distribution System.

Cook, R.F.(1961). Optimizing the application of shunt capacitors for reactive-volt Ampere control and loss reduction, AIEE Trans. PAS, pp. 430-444.

Cook, R.F. (1964). “Calculating loss reduction afforded by shunt capacitor application”, IEEE Trans. PAS, pp.1227-1230.

Glover, J.D. and Sarma, M. (1994). Power System Analysis and Design, 2nd ed., PWS Publishing Company, Boston

Grainge, J.J. and Lee, S.H. (1981). Optimum size and location of shunt capacitors for Reduction of losses on distribution feeders, IEEE Trans. PAS. 100:1105-1118

Pabla, A.S. (2000). Electric Power Distribution, Tata McGraw- HiIl, New Delhi.

Ponnavaiko, M.and Rao K.S.P.(1982).Optimal Distribution System Planning, IEEE Transactions on PAS.50:2969-2977

Saadat, Hadi.(2006). Power System Analysis, McGraw-Hill Publishing Company Limited, New York pp 189-237.