Optimal Capacitor Placement and Sizing for Loss Minimization and Voltage Profile Inprovement Using Genetic Algorithm: A Case Study of the Electricity Company of Ghana

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***Abstract*— Power distribution is the final link between the transmission line and the consumer line. The modern power distribution network is constantly being faced with an ever growing load demand, this increasing load can make the system prone to instability and security threat by causing system burden and voltage dip. Furthermore, even in certain industrial areas under critical loading conditions, it may lead to voltage collapse. This decrease in voltage is mainly due to insufficient amount of reactive power.**

Therefore to improve the voltage profile so as to avoid voltage collapse, reactive power compensation is required. It is well known that losses in a distribution system are significantly higher compared to that in a transmission system. The need for improving the overall efficiency of power delivery has forced the power utilities to reduce the losses at distribution level. Many arrangements like networking reconfiguration, shunting capacitor placement, etc can be worked out to reduce these losses. Shunt capacitors supply part of the reactive power demand, thereby reducing the current and MVA in lines. Installation of shunt capacitors on distribution networks will help in reducing energy losses, peak demand losses, improved system voltage, improved system stability and improved power factor. In light of the above-mentioned facts, the objective of this project is to reduce losses and improve voltage profile based on Genetic Algorithm optimization technique in the distribution network of the Electricity Company of Ghana. However, the optimal achievement of our objective should take into account the size and location of the capacitor to be installed.

Distribution system is mostly radial; this factor contributes to the drop in voltage as one moves along a radial feeder. Loss minimization and voltage profile improvement is an important aspect in all the three major sections in power system engineering. This paper proposes a method of placing shunt capacitors at fixed places in a typical Feeder of the electricity company of Ghana (ECG) to ascertain its impact on loss minimization and voltage drop issues while paying attention to cost benefit analysis in the. Loss minimization helps to improve the overall efficiency and frees up the system for higher capacity. Three major sections have been employed in this paper. Loss sensitivity analysis is use to identify the buses that are most sensitive to the system losses while BIBC BVBC method of load flow analysis is used for the system load flow due to the radial nature of our case study. Finally, Genetic algorithm is used to optimally place capacitors for the overall intended achievement. This work is done on iterative algorithms in a MATLAB environment to arrive at the optimal solution.

***Index Terms*— Capacitor bank, Genetic algorithm, reactive power, ECG distribution system, optimal capacitor placement, Feeder, BIBC BVBC, LSF**

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I. INTRODUCTION

Many recent examples show that voltage instability can be the cause of a major blackout and with the restructuring of the power market; the voltage stability has become a major concern. We realized that as the losses increase, voltage tends to reduce and this goes a long way to affect the overall efficiency of the system with the final effect of instability and loss in revenue. Not only is the cost of electricity a major concern in recent times but also, as I write this paper, the ECG is undertaking a load shedding exercise in the country to make up for the demand deficit. If there is anything that can be done to recoup some part of the power loss in distribution, it will help reduce the deficit and also improve demand side management. Hence, the need to make this kind of research. The literature on distribution system is very much diversified; the brief review is presented on the subject of capacitor placement in the distribution system. The primary and main function of electric utilities is providing a reliable and secure energy supply for customers with specific voltage and stable frequency. So, they try to obtain this goal by means of different solutions.

One of the most effective and useful methods in reducing the power losses of distribution networks is utilization of optimal shunt capacitors compensation. Technological progress, Economical analysis and Environmental consideration are the efficient reasons why distribution networks of power systems are generally compensated to minimize the VAR flow so that reliable demands can be met. Proponents on this field have proposed various theories in dealing with this vast subject, and a review of some of their works is worth reflective and informative. Optimal sizing of capacitors placed on a radial distribution system is explained by M. e. Baran and F.F Wu in reference [1]. The capacitor-sizing problem is a special case of the general capacitor placement problem. The optimal capacitor placement problem is to determine the location and size of capacitors to be placed in a power distribution networks in an efficient way to reduce the power losses and improve the voltage profile of the system [2]. OmPrakash Mahela *et al.* [4] presented different techniques of capacitor placement in transmission and distribution system to reduce line losses and voltage stability enhancement. Power losses can be separated to active and reactive component of current branch, where the use of shunt capacitors for VAR compensations can be use to reduce the losses produced by reactive current [4]. VAR compensation is defined as the management of reactive power to improve the performance of AC power systems. The concept of VAR compensation embraces a wide and diverse field of both system and customer problems, especially when power quality issues can be attenuated or solved with an adequate control of reactive power.

There are many ways for capacitor placement and determination of size of capacitors in power systems. References [7]-[9] have considered capacitor placement in power networks using Genetic Algorithm for optimization, [10]-[12] have considered Particle Swarm Optimization technique, [13] has considered Plant Growth Optimization, [14] has considered the Game Theory, [15]-[16] have considered Ant Colony Optimization, [17] has presented a MATLAB based approach for optimal capacitor placement for loss reduction in radial distribution feeder and [18] has considered Body Immune Algorithm for optimal Placement of Capacitors. Major benefits are due to reduction in KVA input, KW demand and energy loss. His work was a success even though optimization was not considered. Milosevic, B., Begovic, M. [7] presented a capacitor placement for conservative voltage reduction on distribution feeders with the use of analytical tools such as optimal power flow, voltage stability analysis, reliability analysis, etc. Moreover, it can be controlled by the installation of devices such as fixed and controlled capacitors banks, transformer with On-load Tap Changers (OLTCS) etc. Sundhararajan, S., Pahwa, A, present a new design methodology for determining the size, location, type and number of capacitors to be placed on a radial distribution system is presented in reference [9].

The objective is to minimize the peak power losses and energy losses in the distribution system considering the capacitor cost. A sensitivity analysis based method is used to select the candidate locations for the capacitors. A new optimization method using Genetic Algorithm is proposed to determine the optimal selection of capacitors. Text results have been presented along with the discussion of the algorithm. A simplified Network approach to the VAR control problem for radial distribution system is considered in reference [10]. According to this method proposed by M.M.A Salam and A.Y. Chikhani; the capacitors are assumed to be located optimally at the feeder branches. The optimal compensation levels (capacitor size) are represented by dependent current sources located at the branch-connected bus. The solution of the equivalent circuit for distribution system yields the values of the voltage at any bus. The actual compensation level is then determined by substituting the bus voltage in the dependent current source formula. The method is simple and needs no sophisticated optimization technique. It can be used as on-line controller and as well as in the planning stage. It can be easily adapted in the expert system configuration. Cook [13] considered the effects of fixed capacitors on radial distribution network with distributed loads and considered the reduction in energy loss. A methodology has been used to determine the ratings and location of fixed capacitors on the radial feeder for periodic load cycle. Cook also in reference [14] considered fixed and switched capacitors and discussed the methodology to decide the timing for operation of switched capacitors. Shirmonhammadi *et al*. [16] has proposed a load flow method for distribution network using a multi-port compensation technique and basic formulations of Kirchhoff's laws. Rajicic [18] has modified the fast decoupled load flow method to suit high R / X ratio nature of distribution system. Various methods [16-21] have been reported for the load flow of radial distribution system. Gosh and Das [19] have proposed a method for the load flow of radial distribution network using the evaluation based on algebraic expression of receiving end voltage. Teng [21,22] has proposed the load flow of radial distribution system employing bus-injection to branch-current [BIBC] and branch-current to bus voltage (BCBV) matrices. Our work seeks to employ BIBC and BCBV matrices approach Ref [23] proposed an approach for capacitor placement through sensitivity factors and self-adaptive hybrid differential evolution (SaHDE) technique. In this paper, the genetic algorithm is applied to determine the optimal location and size of a distribution generation unit along with four shunt capacitors for power losses reduction, voltage profile and reliability improvements.

II. THE PROPOSED SYSTEM OF THE ECG POWER DISTRIBUTION SYSTEM

The Electricity Company of Ghana is the largest power distribution company in Ghana. The company under takes its power distribution activities in the six out of ten major regions in Ghana. In Ghana, power generation is done by the Volta River Authority (VRA) and transmitted through an independent transmission company known as the Ghana Grid Company (GRIDCo). ECG takes over the process from GRIDCo for the final power distribution to the consumers. High power losses are one of the serious challenges in the distribution systems in Ghana. Losses in the distribution system was 25.1% by the close of 2011 [23] and researches show that a lot more of the power produced in the system go wastes as ohmic losses [20]. Due to the wide and complex nature of ECG's system, a section of their Feeders have been chosen for this study. In its distribution network, minimum values of LT shunt capacitor banks ranging from 300-500(kVar) located at the main substations consisting of two sections connected in parallel but controlled by different isolators are used. In the ECG power grid, LT shunt capacitor banks are normally installed at the substations where GRIDCo steps down voltage from 161kV to 33kV. The proposed study considers that the LT shunt capacitors should not be allocated according to thumb rule rather should be placed on the basis of reactive power requirement of the system which ultimately depends on nature of load connected along the Feeders. One complete Feeder C61 in the single line diagram below is chosen for this study

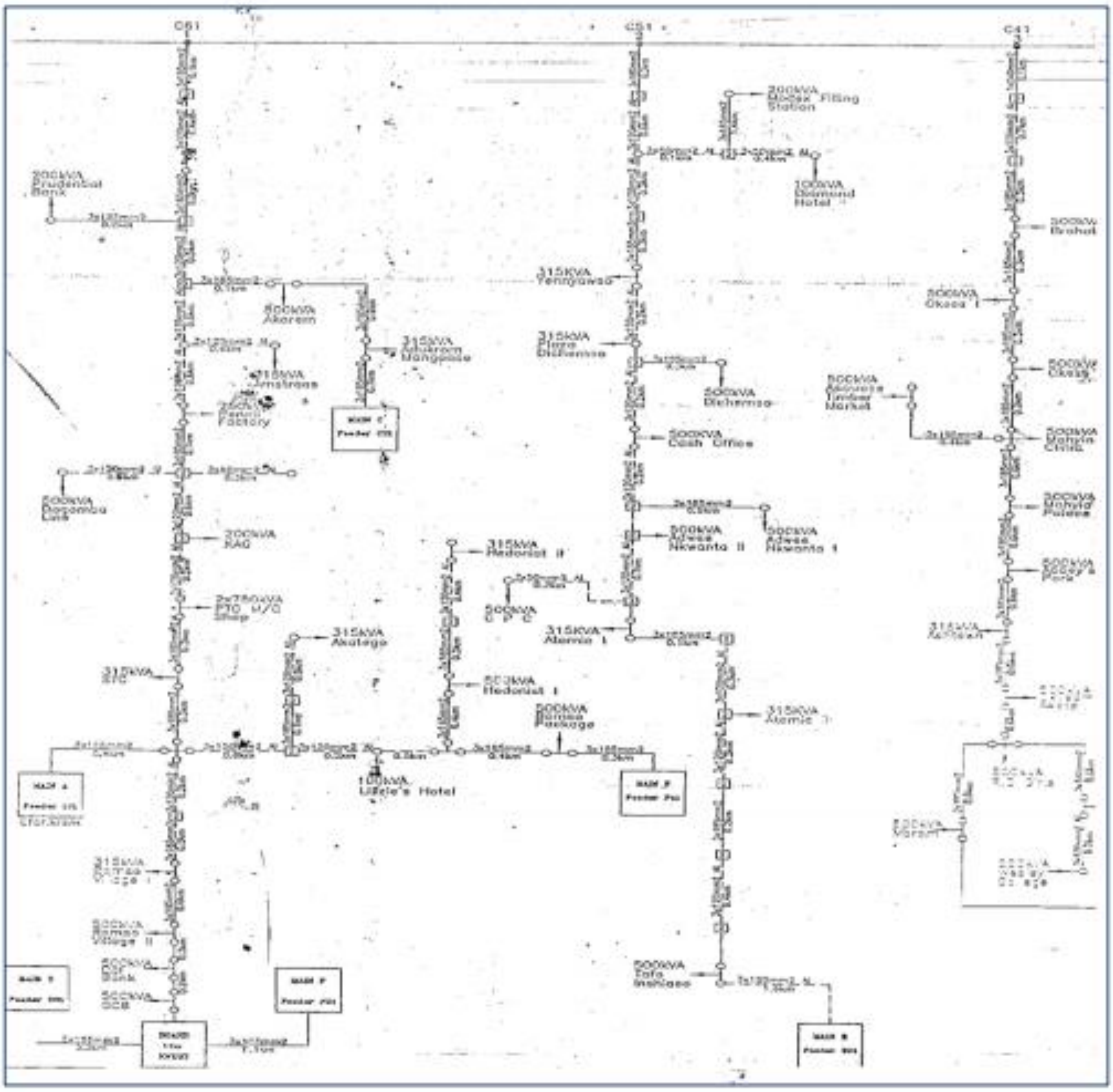


Fig 1 single line diagram of proposed system

Problem formulation

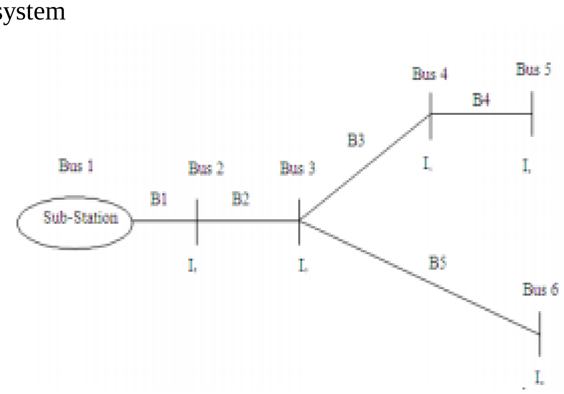
The main aim for placing a capacitor in a power utility network is to give reactive power support that will help in loss minimization and voltage profile improvement. Minimizing the distribution power loss and improvement of voltage profile by optimally placing capacitors at fixed location in the ECG system while paying attention to the cost of purchasing and installing a capacitor will formulate our objective function. Load flow, Formulation of the objective function, constrains, power loss calculations and loss reduction are explain in the section below [2]

Load flow in a radial distribution system

Distribution system are mostly radial in nature and the well known methods like the Newton-Raphson and the Gauss-Seidel methods are not normally found suitable mainly because of the difficulties in convergence of the iterations and the large memory requirement of the computer. In this paper, the BIBC BCBV method of solving load flow for a radial distribution network is used.

A simple radial network is used to help illustrate the formation of a BIBC and a BCBV matrix

Fig 2 A typical radial distribution system



$B5 = I6,$ (3.3)

$B4 = I5,$ (3.4)

$B3 = I4 + I5,$ (3.5)

$B2 = I3 + I4 + I5 + I6,$ (3.6)

$B1 = I2 + I3 + I4 + I5 + I6,$ (3.7)

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix}$$

[B] = [BIBC] [I] (3.9)

And for a BCBV matrix,

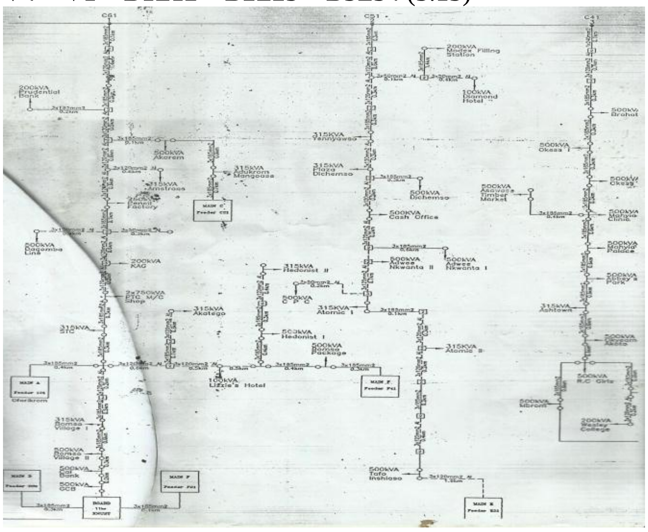
V2 = V1 – B1Z12,

V3 = V2 – B2Z23,

V4 = V3 – B3Z34,

Substituting these eqs into each other results in the equation below

V4 = V1 – B1Z12 – B2Z23 – B3Z34 (3.13)



[ΔV] = [BCBV][BIBC][I]

[DLF] = [BCBV][BIBC]

[ΔV] = [DLF][I]

The solution for the load flow can be obtained by solving eqs. (3.19) and (3.20) iteratively which are given below:

$$I_i^k = I_i^r(V_i^k) + j * I_i^i(V_i^k) = \left(\frac{P_i + j * Q_i}{V_i^k}\right) \quad (3.19)$$

$$[\Delta V^{k+1}] = [DLF][I^k] \quad (3.20)$$

$$[V^{k+1}] = [V^o] + [\Delta V^{k+1}] \quad (3.21)$$

Objective function

The objective function of the problem is to cost effectively minimizing the loss and voltage deviation.

Where

- Cci is the constant installation cost of capacitor and Circuit breaker.
- Ccv is the rate of capacitor per kVAr.
- Qck is the rating of capacitor on the system bus in kVAr.
- Eli is the energy lost in a branch
- Ce is the energy rate

This function mathematically is;

$$S = C_e \times \sum_{i=1}^{n} EL_i + \sum_{k=1}^{ncap} C_{ci} + (C_{cv} \times Q_{ck}) \quad (4.5)$$

Selection of sensitive buses for compensation

Consider a distribution line with load and impedance

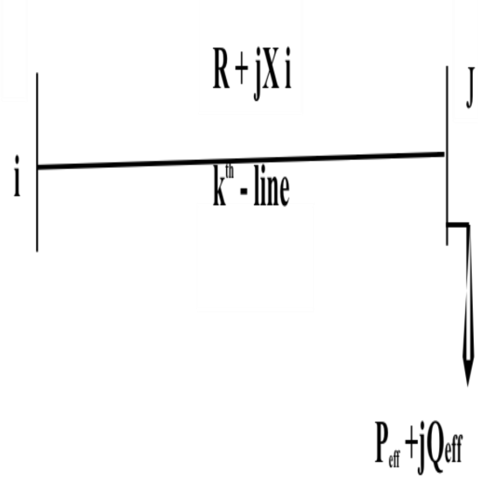


Fig 3. A distribution line with impedance load

Real power loss in the line is given by

$[Ik]^2 * [Rk]$, which can also be expressed as

$$P_{lineloss}[j] = \frac{(P_{eff}^2[j] + Q_{eff}^2[j]) * R[k]}{(V[j])^2} \quad (4.7)$$

$$Q_{lineloss}[j] = \frac{(P_{eff}^2[j] + Q_{eff}^2[j]) * X[k]}{(V[j])^2} \quad (4.8)$$

Peff [j] = Total effective active power supplied beyond the bus 'j'

Qeff [j] = Total effective reactive power supplied beyond the bus 'j'

Now, the Loss Sensitivity Factors can be calculated as:

$$I_i^k = I_i^r(V_i^k) + j * I_i^i(V_i^k) = \left(\frac{P_i + j * Q_i}{V_i^k}\right) \quad (3.19)$$

$$[\Delta V^{k+1}] = [DLF][I^k] \quad (3.20)$$

$$[V^{k+1}] = [V^o] + [\Delta V^{k+1}] \quad (3.21)$$

III. GENETIC ALGORITHM

Developed by Prof. John Holland at the University of Michigan in 1975 and latter developed by his student [6] the central theme of genetic algorithm has been robustness which is essentially based on the theory of natural selection, the process that drives biological evolution. In optimization, robustness means the balance between efficiency and efficacy [16]. The difference between GA and other traditional optimization methods are,

- GAs work with the coding of the parameter set, not the parameters themselves
- GA's search for a population of points, not a single point
- GA's use the objective function information and not the derivative or second derivative
- GA's use stochastic transition rule, not deterministic rules

Each solution is represented by a string of binary variables corresponding to chromosomes and genetics. Zeros and ones represents each solution. The fitness term in genetics is equivalent to the objective function i.e. the numerical value of the objective function corresponds to the concept of fitness in genetics. After trial solutions are selected, a new generation (a new set of strings) is produced by selecting, using stochastic principle, the fittest parents to produce children from among the trial solutions

Following are important terminology of genetic algorithm in connection with this paper:

Individual: an individual is a combination of capacitor values that can be applied to the objective function for a certain results. It is basically the set of values of all the variables for which function is going to be optimized. The value of the objective function for an individual is called its score. An individual is sometimes referred to as a genome and the vector entries of it as genes.

Population: a group of individuals make up a population. For example, if the size of the population is 100 and the number of variables in the objective function is 3, a 100-by-3 matrix in which each row can represent an individual, is known as a population.

Generation: in a standard procedure, the genetic algorithm performs a series of computations on the current population to produce a new population by applying genetic operators for all iteration. Each successive population is called new generation.

Parents and children: to create the next generation, the genetic algorithm selects certain individuals in the current population, called parents, and uses them to create individuals in the next generation, called children.

The following genetic operators are applied on parents to form children for next generation**:**

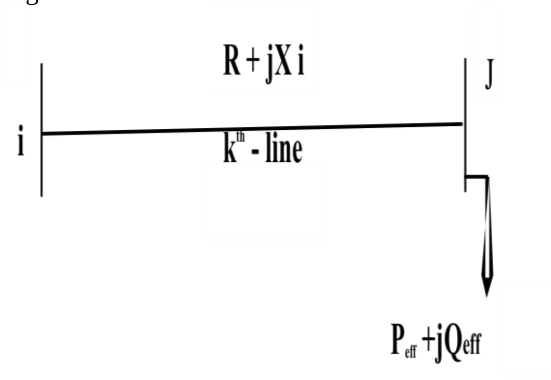
Reproduction: selects the fittest individuals in the current population to be used in generating the next population. The children are called Elite children.

Crossover: causes pairs of individuals to exchange genetic information with one another. The children are called crossover children.

Mutation: causes individual genetic representations to be changed according to some probabilistic rule. A mutated child can have its binary string changed from zero to one or vice-versa.

In this paper for the purpose of optimal capacitor placement in the electric transmission network for loss reduction and minimizing total annual cost, genetic algorithm technique has been applied. The main computational steps of the proposed algorithm is shown in the flow chart below:

proposed algorithm is shown in the flow chart below:



IV. RESULTS AND DISCUSSIONS

In all simulations, the following parameters have been used:
1. Population size = 100
Capacitor value has been taken as a discrete variable. The capacitor allowable range is from 5 kVAr to 255kVAr with discrete step, this is due to the number of binary digits (eight) used for decimal conversion for the GA crossing. In this case first three buses having the highest loss sensitivity values are selected as candidate buses, these candidate buses are (*i.e. buses 2, 9, 12*) and the capacitor sizes have been determined by using GA.

After three potential buses have been selected using the LSF, the capacitor values to be installed at these bus locations is done using the genetic algorithm. A comparison is made between the losses with capacitor values installed at these potential buses and without capacitor installed at these buses (i.e. before compensation). The capacitor combination with the least loss value is chosen for final installation GA Output Best capacitor combination for the least losses is represented in the table below

X_1	X_2	X_3	Loses without Capacitors	Losses with Capacitors
245	20	253	384kW	134kW

Table (1): Comparison of losses with and without capacitor

X_1	X_2	X_3	Loses without Capacitor (kW)	Loses with Capacitor (kW)
26	255	255	384	139.5
238	20	241	384	136.5
232	10	218	384	139.8
179	24	242	384	144.5
255	53	43	384	156.6
246	10	48	384	157.6
226	14	219	384	140.9
253	248	5	384	153
151	62	245	384	148.1
253	34	222	384	136.5
201	11	9	384	174.9
7	225	253	384	143.5
26	39	219	384	164.9
48	107	102	384	175.3
231	105	126	384	154.2
250	254	219	384	142.6
230	55	180	384	147.4
245	20	253	384	134
232	68	105	384	155.9
156	75	207	384	154
206	31	241	384	141.6
77	20	255	384	152.8
135	73	212	384	155.4
87	163	186	384	160.3
243	34	226	384	138.7

It can be seen that the placement of a 254kVar at bus 2, 20kVar at bus 9 and finally 253kVar at bus 12 gives the least losses and most improved voltage levels.

Table (2) Results of Load Flow Solutions of 12 Bus ECG Feeder (with optimal capacitor at three Candidate buses)

Minimum system voltage V12 = 0.9635 p.u at bus 12

Bus Number	Name	Voltage Magnitude in p.u	Angels in degrees	Capacitor value 'Q' in kVAr
1	C51	1	0	0
2	Modex	0.9796	-0.048	245
3	Yenyawso	0.9763	-0.054	0
4	Plaza	0.9751	-0.057	0
5	Dichemso	0.9738	-0.059	0
6	Cash Office	0.9728	-0.062	0
7	Adwee Nkwanta I	0.9702	-0.069	0
8	Adwee Nkwanta II	0.9695	-0.072	0
9	CPC	0.9664	-0.085	20
10	Atomic I	0.9648	-0.089	0
11	Atomic II	0.9642	-0.091	0
12	Tafo Nhyieso	0.9635	-0.095	253

$$Q_{lineloss}[j] = \frac{(P_{eff}^2[j] + Q_{eff}^2[j]) * X[k]}{(V[j])^2} \quad (4.8)$$

Fig.1 a graph of voltage profile before and after compensation

	Before Compensation (ECG System)	After Compensation (ECG System)
Minimum system voltage (p.u)	0.9575	0.9626
Power Loss (kW)	384kW	134kW
Loss reduction in (%)	0%	65.10%
Capacitor location and size (kVar)	N/A	Bus 2-----245 Bus 9-----20 Bus 12---253
Total kVars installed	N/A	245+20+253=518 (kVar)
Total Energy Loss Cost	$41,476	$14,472
Revenue generated from saved energy		$41,476-$14,472 = $27,004
Total Capacitor cost	N/A	$140,900
Total amount of capacitor with 30% interest per annum to be paid		$183,170
Loan can be paid in 7 months	---------------	(183,170/27,004) =6.78 7 months

Table(3). The above table analyzes cost recoupment and future profits.

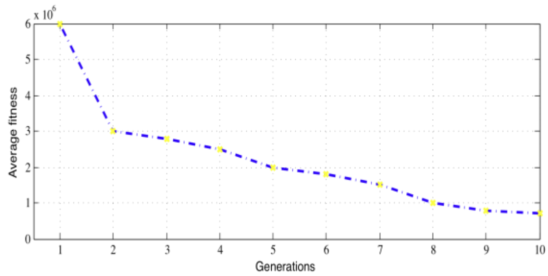


Fig 3. A graph of generations against number of iterations

V. CONCLUSION

Its been proven from the above works that the ECG can not only reduce their Distribution losses and improve the system but also, make serious financial gains by investing in such projects. From table 3, its clear that even if a loan facility is acquired for the purchase of capacitors, it can be paid in less than a year and the subsequent years will be profits from that investment. This work has been presented to the management of the ECG for further considerations and future plans.

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