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Power Loss Reduction in Distribution Systems through an Intelligent Method Considering Operational Costs

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ABSTRACT

A considerable amount of energy produced by a power plant is lost on its way to the customer. This has always been one of the most important problems facing power industry. Given the fact that distribution networks are extended, most of power loss takes place in such networks. Many methods have been used for reducing power loss, but each of the papers previously published on this subject have focused on one or two of such methods. In this work, different ways of reducing power loss were investigated both individually and together using an intelligent method and considering attendant costs. The paper proposes an innovative method for estimating the cost of adjusting imbalance of a three-phase system. The objective function aimed to minimize the costs associated with adjusting load imbalance, determine optimum placement and size of fixed capacitors, and remove inappropriate transformers, dilapidated conductors, and loose connections. Maximizing the financial gain from power loss reduction was another consideration. Five ways of reducing power loss in an actual feeder were compared and prioritized considering operational costs. The findings indicate that, regarding the amenities available in the feeder under study, adding capacitors and adjusting load imbalance are the most efficient and cost-effective ways of reducing loss. What is more, the present work seems to be a forerunner in that it takes account of the cost of adjusting load imbalance.

KEY WORDS: Loss reduction, Load imbalance correction, capacitor placement, dilapidated transformers, dilapidated conductors, loose connections

1) INTRODUCTION

Energy preservation is of utmost importance considering environmental issues, the high cost of fossil fuels, formation of privately-owned power utilities, and the expenses and time required for developing power plants.

Much government-funded investment has been made into reducing energy loss in different areas, including electrical energy. Reducing power loss at the distribution level has attracted the most attention because of the high amount of loss at this level. This, coupled with massive investment, means that even the smallest change in the way a network is developed or optimized could result in substantial changes in the financial status of power distribution utilities.

Like consumption, power loss requires an increase in power plant capacity, especially at peak hours, thus demanding much investment. Obviously, loss implies that a considerable amount of the generated energy is wasted rather than sold to the customers. This imposes many charges on power utilities and ultimately on power industry.

Power loss is a function of various factors and components. The main components of loss in a distribution network are summarized in [1] as follows:

- Ohmic loss in the conductors of primary and secondary network.
- Ohmic loss in the windings of distribution
- Iron loss in the core of distribution transformers.
- Ohmic loss in service cables between secondary feeders and customers.
- Ohmic loss in leakage currents of shunt equipment, such as insulators and arrestors.

A wide variety of methods have been proposed and tested over the past few decades for reducing power loss. Ref. [1] provides a list of such methods applied to the distribution level:

- Reconductoring in primary and secondary feeders.
- Feeder reconfiguration.
- Using high efficiency distribution transformers.
- Reduction of secondary network length with larger number and optimal location of distribution transformers.
- Using distributed generation.
- Subtransmission substations placement near load centers.
- Load balancing between three phases and feeders.
- Load factor improvement with demand side management strategies.
- Voltage upgrading.

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Each way of reducing loss results in the reduction of one or more of the causes of loss. Unbalanced loads increases power loss in lines and transformers. Correcting this imbalance results in loss reduction. Optimally placing a capacitor in a distribution network improves voltage profile, increases the usable capacity of the network, corrects the power factor, decreases line currents, and reduces power loss. Due to overwork-induced dilapidation, a transformer causes much copper and iron loss. Replacing the transformer reduces these kinds of loss, ultimately reducing network loss. The cables and conductors in the network wear down because of weather conditions, and this increases their resistance and in turn increases power loss. Network connections loosen with the passage of time, resulting in power loss. Correcting such connections reduces resistance of the line and power loss.

The methods used to reduce loss in distribution systems can reduce part of the network loss depending on network typology. Another factor influencing the effectiveness of a loss reduction method is the type of the network. And sometimes a method reduces loss, but only at a great cost. Therefore, the best method of reducing loss in is one that is cost-effective for the distribution system under study.

A review of previous works on power loss reduction follows.

Ref. [2] tried to reduce loss by removing load imbalance. The loss reduction method used by [3] was balancing transformer load taking account of the cost recovery period.

One of the methods used in loss reduction has been capacitor placement. For instance, [4] used evolutionary fuzzy programming algorithm and dynamic information structure to determine the optimum place for capacitors in a 69-bus radial distribution system. Ref. [1] used Genetic Algorithm (GA) for capacitor placement in a 69-bus system. Ref. [5] placed capacitors using the Particle Swarm Optimization (PSO) algorithm. Operational costs associated with capacitor placement were taken into account in [6] and [7].

Ref. [8] found that loss in a transformer reduces when the transformer works at half of the nominal load and if harmonics filters are installed.

Ref. [9] proposed an algorithm for deciding on the optimal conductor for a radial distribution system. Using a new load flow, the method also aims to reduce loss in the network.

In [10], an investigation was made into the effect of fixing loose connections on loss reduction in Hormozgan power network in Iran considering operational costs involved.

Some authors have combined different reduction methods. For example, [11] used reconfiguration and capacitor control in a 119-bus system. Network reconfiguration and capacitor placement were jointly used by [12]. Loss reduction was attempted in [13] through capacitor placement and voltage adjustment.

What all the papers reviewed have in common is that each used only one or two methods for reducing loss. Additionally, the researchers who attempted to reduce loss by fixing load imbalance did not disclose the method of calculating the costs [2, 3].

The present paper is an attempt to determine the best method of reducing power loss with regard to the costs involved and the amount of loss reduction. For this purpose, using the GA, an objective function was optimized, with six different considerations in mind: adjusting load imbalance, determining optimum capacitor size and placement, removing inappropriate transformers, replacing dilapidated conductors, correcting loose connections, and maximizing potential financial gain resulting from loss reduction.

For this purpose, the load current of different transformers in an actual feeder was measured. Then, the above-mentioned ways of loss reduction were employed to find out about the operational costs and benefits (i.e., loss reduction) associated with them, both discretely and collectively. GA was used to optimize the objective function.

The present work is innovative in two ways:

- Simultaneous employment of five ways of reducing loss, considering the costs associated with each method
- Proposing a new method for determining the cost of adjusting load imbalance.

2) Model formulation and Problem statement

a) Model formulation

Different methods are used to balance transformer loads. These methods attempt to bring the currents associated with the phases of each load closer to the average current [2, 3].

Placing capacitors is an effective method of reducing power loss in a network and is carried out in numerical, analytical, heuristic, or more recently intelligent methods [1, 4-7]

The loss of distribution transformers can be reduced in several ways: using better quality materials, half loading, and using harmonic filters [8], to name but a few.

Two effective ways of reducing the loss of lines are using appropriate conductors [9] and fixing loose connections [10].

i) <u>Fixing load imbalance</u>

As it was mentioned above, fixing load imbalance requires the current of each phase to be close to the average current of the three phases.

ii) <u>Capacitor placement</u>

Capacitors were placed with the following in mind:

- Capacitors were only placed where loads were.
- Loads were adjusted prior to capacitor placement.
- Use was made of 12.5-kvar capacitors. The number of capacitors was determined by GA.
- A gene was considered for each load.

- The total number of capacitors multiplied by the price of each capacitor and the fixed costs associated with capacitor placement were added up in the objective function
- Fixed costs in this work were of three types: (a) 1-6 steps, (b) 7-12 steps, and (c) 13-18 steps.

The maximum number of steps was determined by the transformer with the highest capacity (Eq. (1)).

$$\tan\phi_1 = \frac{Q_1}{P_1} \rightarrow Q_1 = P_1 \tan\phi_1$$
$$\tan\phi_2 = \frac{Q_2}{P_2} \rightarrow Q_2 = P_2 \tan\phi_2 \qquad (1)$$
$$P = P_1 = P_2$$
$$Q_c = Q_1 - Q_2 = P(\tan\phi_1 - \tan\phi_2)$$

where Q_c is the capacity of the installed capacitor.

Given that the transformer operates at its nominal apparent power, then $P_{\max} = 504\,kW$, $\cos\phi_1 = 0.8$, and $\tan\phi_1 = 0.75$.

In this work, since the aim is to increase the power factor from 0.8 to 0.955, the capacitor to be installed in the feeder will have a maximum capacity of 222 kvar.

The cost of capacitor placement for the entire network is calculated from Eq. (2). Also, the cost of capacitor placement for each bus is calculated from Eq. (3). In addition, Eq. (4) calculates the variable cost of placing capacitors for each bus.

$$C_{cap} = \sum_{i=1}^{i=n} C_{cap-i} \qquad (2)$$

where:

- C_{cap-i} : cost of placing capacitors on the ith bus

$$C_{cap-i} = C_{cap-fixd-i} + C_{cap-\mathrm{var}\,iable-i} \qquad (3)$$

where:

- $C_{cap-fixd-i}$ fixed cost of placing capacitors on the ith bus
- $C_{cap-\mathrm{var}\,iable-i}$ variable cost of placing capacitors on the ith bus

$$C_{cap-\mathrm{var}\,iable} = n_{cap} \times p_{cap} \qquad (4)$$

where:

- n_{cap} : number of capacitors on the ith bus
- p_{cap} : price of each capacitor

iii) <u>Replacing dilapidated transformers</u>

Dilapidated transformers were replaced as follows:

- The transformers used in the feeder under study had the following apparent power values: 25, 50, 100, 200, 250, 315, 500, 630 kVA.
- A gene was considered for each transformer.
- If a transformer is replaced, its copper and iron losses decrease by 20%, according to Qazvin Power Distribution Company.
- Finally, the costs associated with replacing all transformers were added up so that the total cost of transformer replacement was known.

The cost of transformer replacement is the sum of all the expenses associated with replacing the transformers, as determined by GA.

iv) <u>Replacing dilapidated lines</u>

Dilapidated lines are replaced as follows:

- A gene was considered for each line.
- If a line is replaced, its resistance decreases by 10%, according to Qazvin Power Distribution Company.
- Eventually, the costs associated with replacing all dilapidated lines were added up so the total cost of line replacement was known.

The cost of conductor replacement is the sum of all the expenses associated with replacing the conductors, as determined by GA.

v) Correcting loose connections

Loose connections in the network were corrected as follows:

- The length of the lines connecting buses was calculated by computer software.
- It was assumed that there was a connection at each end of each line.
- A connection was added if the line connecting two buses was longer that 480 m.
- A gene was considered for each connection.
- The assumed number of connections holds true of single-wire lines only. For three-wire lines, the number should be multiplied by three.
- If a loose connection is corrected, line resistance decreases by 0.001 ohms, according to Qazvin Power Distribution Company.
- Lastly, to calculate the total cost of correcting loose connections, the operational costs associated with correcting each connection was multiplied by the total number of connections (Eq. (5)).

$$C_{connection} = n_{connection} \times p_{connection} \tag{5}$$

where:

- $n_{connection}$: total number of loose connections
- $p_{connection}$: cost of fixing each loose connection

vi) The benefit obtained from loss reduction

The benefit obtained from reducing power loss is calculated from Eq. (6).

$$B_{loss\_reduction} = (P_{loss-after} - P_{loss-before}) \times 8760 \times LSF \times p_{energe} \tag{6}$$

where:

- $P_{loss-after}$: loss after methods were applied
- $P_{loss-before}$: loss before methods were applied
- LSF : loss factor
- p_{energe} : price of energy

b) Problem statement

As it was discussed in the previous section, past research failed to formulate a model for calculating the cost associated with correcting load imbalance and to simultaneously apply all the methods. Both problems were dealt with in the proposed method described in the next section.

The following problems were taken into account:

1) Adjusting load imbalance according to the rate of imbalance and the cost associated with adjustment.
2) Determining optimum locations and sizes
3) Identifying dilapidated transformers to be replaced
4) Identifying the length of dilapidated line to be replaced
5) Identifying loose connections to be corrected

It is worth noting that operational costs and network constraints were observed all along.

3) NEW METHOD

a) Fixing load imbalance

Load imbalance was adjusted as follows:

- The percentage of imbalance was determined for each phase (Eq. (7)).
- A certain percentage (from 0 to 100) was randomly assigned to each load by GA.
- The cost of imbalance correction for each phase is equal to the integral of the area under the curve of the A/x graph in the interval $[a_{new}, a_{old}]$.
- The cost of imbalance correction for each load is equal to the sum of imbalance correction costs for the three phases.
- The total cost of imbalance correction is equal to the sum of imbalance correction costs for all the loads in the feeder under study (Eq. (8)).

$$a_{old} = \frac{I_p - I_{ave}}{I_{ave}} \tag{7}$$

Where I_p is the phase current, and I_{ave} is the average of the three phase currents.

$$C_{imbalance} = A\sum_{i=1}^{n} \ln\left(\frac{a_{old-R-i} \times a_{old-S-i} \times a_{old-T-i}}{a_{new-i}^{3}}\right) \tag{8}$$

where:

- $a_{old-p-i}$: old percentage of load imbalance for the pth phase of the ith load
- a_{new-i}: new percentage of load imbalance for the ith load

A is a constant set at $700 according to our empirical work.
It is worth noting that the cost of reducing a load imbalance of 60% to one of 50% is less that the cost associated with decreasing an imbalance of 30% to one of 20% (Fig. 1)

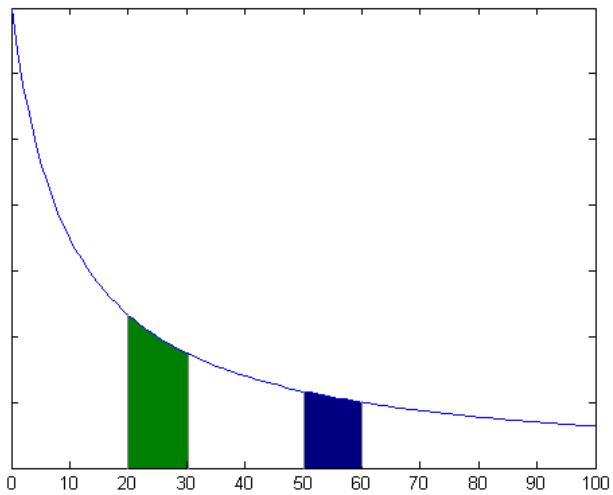

Fig. 1. The A/x diagram

Fig. 2 gives the flowchart of fixing load imbalance.

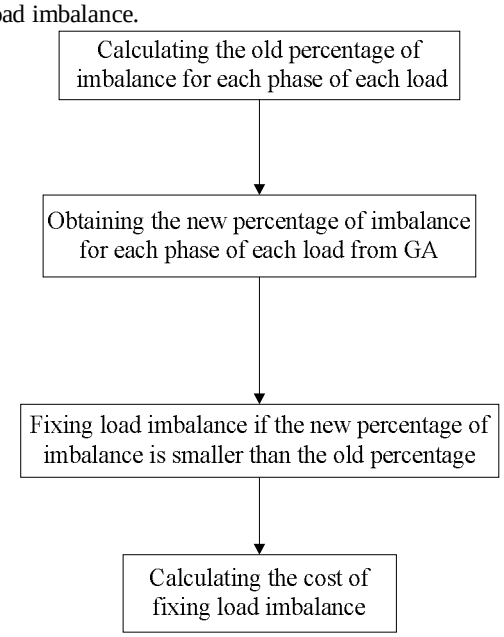

Fig. 2. The flowchart of fixing load imbalance

b) Objective Function

The objective function was defined as Eq. (9) below:

$$OF = C_{imbalance} + C_{cap} + C_{trans} + C_{line} + C_{connection} + B_{loss\_reduction} \quad (9)$$

where:

- $C_{imbalance}$: the cost of adjusting imbalance
- C_{cap} : the cost of capacity r placement
- C_{trans} : the cost of transformer replacement
- C_{line} : the cost of conductor replacement
- $C_{connection}$: the cost of correcting loose connections
- $B_{loss-reduction}$: the benefit resulting from loss reduction

The flowchart of the OF is given in
Fig. 3.

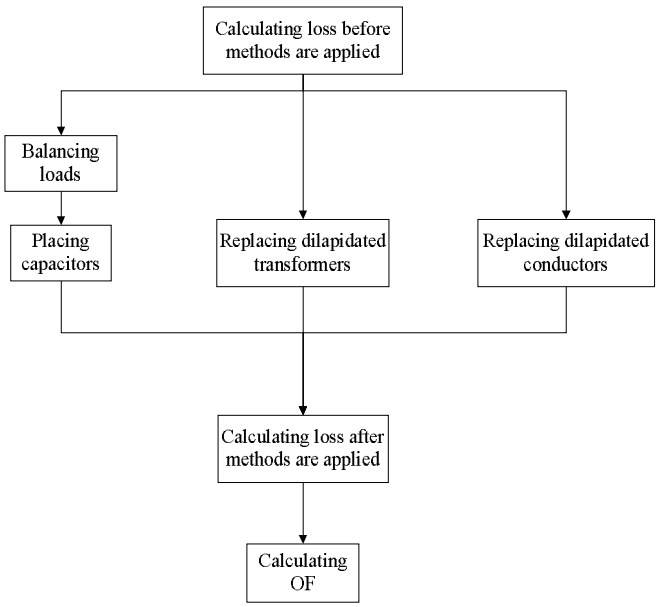

Fig. 3. The flowchart of the OF for each iteration

4) Simulation

a) Case study

The distribution system used in this study was the 20-kV Feeder of Sharif Abad in northwestern Iran.
Fig. 4 is the schematic represenation of this feeder, and
Fig. 5 is an expansion of part of
Fig. 4.

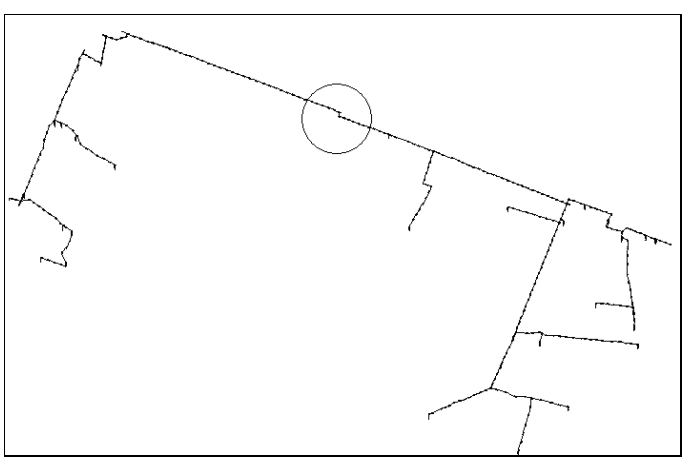

Fig. 4. The schematic representation of Sharif Abad Feeder

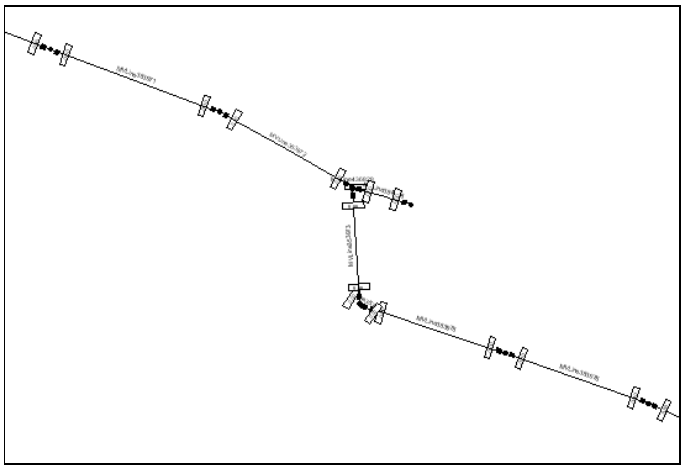

Fig. 5. The enlargement of the area marked in Fig. 4.

The specifications of the feeder under investigation are given Table 1 and Table 2 below.

Table 1: A sample of the length of line between every two terminals

Terminal i	Terminal j	Length (km)
T59	T60	0.04658
T60	T61	0.042101
T62	T63	0.081154
T64	T65	0.05293
T65	T66	0.054265
T66	T67	0.058357
T67	T68	0.068757
T68	T69	0.073169
T69	T70	0.062034
T70	T71	0.036182
T71	T72	0.034367
T72	T73	0.063003
T73	T74	0.024233
T74	T75	0.061842
T75	T76	0.073207
T76	T77	0.065371

Table 2: The type of the conductors used

Type	$R(\Omega/km)$	$X\ (\Omega/km)$	$W\ (kg/km)$
1	0.2712	0.2464	450
2	0.4545	0.2664	255

Load current was measured at different points in the feeder (Table 3). In this table, Rows 1-19 were estimated on the basis of measuring the triple-phase current going into the feeder, calculating the total capacity of transformers, and measuring the triple-phase currents of transformers at three points in the feeder. Measuring Rows 20-28 showed them to be balanced.

Table 3: Specifiction of loads

Number	Apparent Power	Bus Number	$I_{ave}(A)$	$I_R(A)$	$I_S(A)$	$I_T(A)$
1	630	T52	968.58	678.006	774.864	1452.87
2	500	T56	768.72	538.104	614.976	1153.08
3	315	T12	484.29	339.003	387.432	726.435
4	315	T14	484.29	339.003	387.432	726.435
5	315	T20	484.29	339.003	387.432	726.435
6	315	T38	484.29	339.003	387.432	726.435
7	250	T8	384.36	269.052	307.488	576.54
8	250	T24	384.36	269.052	307.488	576.54
9	250	T26	384.36	269.052	307.488	576.54
10	250	T44	384.36	269.052	307.488	576.54
11	250	T46	384.36	269.052	307.488	576.54
12	250	T50	384.36	269.052	307.488	576.54
13	200	T2	307.49	215.243	245.992	461.235
14	200	T10	307.49	215.243	245.992	461.235
15	200	T40	307.49	215.243	245.992	461.235
16	100	T34	153.74	107.618	122.992	230.61
17	100	T30	153.74	107.618	122.992	230.61
18	50	T28	76.87	53.809	61.496	115.305
19	25	T6	38.44	26.908	30.752	57.66
20	200	T32	149.75	149.75	149.75	149.75
21	200	T42	149.75	149.75	149.75	149.75
22	200	T36	147.95	147.95	147.95	147.95
23	100	T22	135.32	135.32	135.32	135.32
24	100	T4	128.10	128.10	128.10	128.10
25	100	T34	119.22	119.22	119.22	119.22
26	100	T30	113.67	113.67	113.67	113.67
27	100	T18	95.62	95.62	95.62	95.62
28	100	T16	88.41	88.41	88.41	88.41

Then, the peak moment was determined. Subsequently, power loss at the peak moment was calculated. Finally, the loss for the whole year was calculated considering a loss factor of 0.52 according to Qazvin Power Distribution Company.

Table 4 summarizes the operational costs of the methods applied.

Table 4: Operational costs

Item	Cost
Capacitor 12.5 kvar	136.550 ($/unit)
Fixed cost 1	100 ($/unit)
Fixed cost 2	200 ($/unit)
Fixed cost 3	300 ($/unit)
Trans 25 kVA	2266.938 ($/unit)
Trans 50 kVA	2707.938 ($/unit)
Trans 100 kVA	3688.177 ($/unit)
Trans 200 kVA	5602.810 ($/unit)
Trans 250 kVA	5792.808 ($/unit)
Trans 315 kVA	6863.947 ($/unit)
Trans 500 kVA	10352.565 ($/unit)
Trans 630 kVA	11970.326 ($/unit)
Conductor type1	4.092 ($/kg)
Conductor type2	4.246 ($/kg)
Energy	0.180 ($/kWh)

b) Software

In the present work, DIgSILENT Power Factory 13.2 was used for developing the proposed algorithm for the OF and also for analyzing the system. As an advanced software application for simultaneous analysis of power networks and control systems, DIgSILENT is capable of calculating load flow, short-circuit level, active losses of the network, and the network parameters. The main feature of the application, DPL (DIgSILENT Programming Language), makes it very simple to apply the proposed method. The OF was optimized using GA on MATLAB R2008a Software. A text file was used to bridge the two software applications.

c) Optimization technique

For optimization purposes, first a population should be defined. This initial population is formed by binary accidental quantification of chromosomes. The produced population is subsequently subjected to the objective function in order to obtain the fitness of chromosomes. Eq. (10) shows the relationship between the OF and fitness.

$$Fitness = \frac{1}{OF} \tag{10}$$

Then, we need to select chromosomes from the current population for reproduction. For this purpose, two parent chromosomes are picked out based on their fitness values, which are then used by the genetic operators of crossover and mutation to produce two offspring for the new population. In crossover, genetic information between pairs, or larger groups, of individuals is exchanged. The present paper used two-point crossover for recombination. If we only use the crossover operator to produce offspring, one potential problem that may arise is that if all the chromosomes in the initial population have the same value at a particular position, then all future offspring will have this same value at this position. To resolve this problem, mutation is required, a process which attempts to randomly alter some of the genes. This paper used both operators in order to make sure the optimization is global rather than local.

d) Proposed algorithm

In the proposed algorithm, GA determines the following for each load:

- The percentage of imbalance, which is a number between 0 and 100.
- The quantity of 12.5-kvar capacitors, which is a number between 0 and 18.
- In addition, each transformer, line, and loose connection is assigned a value of either 0 or 1, denoting the necessity (1) or lack thereof (0) of replacement/fixing.

The above-mentioned are only done if constraints are not violated. The details of the proposed method are presented below:

1) DIgSILENT writes the zero in the text file to flag the start of the initial calculation. Detecting this flag, GA will not start the associated program.

2) DIgSILENT writes the matrix $\begin{bmatrix} 1 \\ n_{\text{var } s} \\ n_{\text{var } s-imbalance} \\ n_{\text{var } s-cap} \\ population\_size \\ Generation \end{bmatrix}$ in the text file. The first row is the flag which shows the program must start its operation. When the flag is set to 1, GA must run. $n_{\text{var } s}$, $n_{\text{var } s-imbalance}$, and $n_{\text{var } s-cap}$ identify the total number of the genes within the chromosome, those related to load imbalance, and those associate with the capacitors, respectively.

3) GA writes the matrix $\begin{bmatrix} 2 & B_1 ... B_n\, C_1 ... C_n & T_1 ... T_n\, L_1 ... L_m & X_1 ... X_k \end{bmatrix}$ in the text file. In this matrix, B1,…, Bn are the new percentages of imbalance for each load, C_1,…,C_n are the number of 12.5-kvar capacitors for each load, T_1,…T_n are the values of 0 or 1 pertinent to each transformer, L_1, …,L_m are the values of 0 or 1 pertinent to each line, X_1, …,X_k are the values of 0 or 1 pertinent to the loose connections of each line, and Flag 2 indicates that DIgSILENT must restart its operation.

4) Upon seeing Flag 2 at the beginning of the text file, DIgSILENT starts to operate, and calculates the OF using the chromosome given in that file. The application, then, inserts in the text file Flag 3 and the quantity of the OF in the form of a matrix $\begin{bmatrix} 3 \\ OF \end{bmatrix}$, where Flag 3 is an indicator of the temporary termination of the operation of DIgSILENT and the restart of the operation of the GA.

5) If the maximum number of iterations is not reached, the process described above reverts to Stage 3. Otherwise, the process proceeds to Stage 6 below.
6) The GA is finished, so it inserts Flag 4 in the text file, implying the end of the process.
7) Upon seeing Flag 4 in the text file, DIgSILENT realizes that the process is over.

5) RESULTS AND DISCUSSION

This research was aimed to do the following with regard to attendant costs:
1) Adjusting load imbalance
2) Placing capacitors
3) Replacing transformers
4) Replacing line conductors
5) Correcting loose connections
6) All the above carried out together

The feeder under investigation was found to have a power loss of 142.816 kW prior to the research.

a) Adjusting load imbalance

Table 5 presents the results of adjusting load imbalance in transformers.

Table 5: Correcting load imbalance

Quantity	Item
Loss after run	123.463 kW
Loss reduction	19.353 kW
Cost	$1851.213
Benefit	$15868.586
|OF|	$14017.373

The results showed the power loss to be 123.463 kW after load imbalance was fixed, indicating a reduction of 19.353 kW. This reduction is equal to 13.55% of the total loss of the network. The cost of balancing all the loads was obtained from Eq. (8). According to the measurements, the quantity of phase current R was 1.5 times more than that of the average current. The quantities of phase currents S and T were 0.8 and 0.7 times as large as those of the average current, respectively. Phase current R was 50% more than the average current. Phase currents S and T were 20% and 30% less than the average current, respectively. Now, we can reduce the deficit of phase currents S and T to 10% and 20%, respectively, by reducing the surplus of phase current R to 30%. This will cost $112.7. The loss reduction obtained in this way will be 19.353 kW, and the resulting benefit will be $15868.586 per year.

b) Placing capacitors

Capacitors could not be placed unless load imbalance had been adjusted. Therefore, loss should have a different amount before capacitors are placed than before any of the other methods are carried out. Table 6 gives the results of allocating capacitors in the network.

Table 6: Capacitor allocation

Item	Quantity
Loss before run	135.908 kW
Loss after run	104.798 kW
Loss reduction	31.110 kW
Cost	$18330.150
Benefit	$25507.896
|OF|	$7177.746

Different capacitors were installed at different busses as follows:
- 12.5-kvar capacitors at busses T6, T28, T30.
- 25-kvar capacitors at busses T4, T16, T36, T48.
- 37.5-kvar capacitors at busses T12, T18, T26, T54.
- 50-kvar capacitors at busses T10, T34, T50.
- 62.5-kvar capacitors at busses T14, T22, T40, T46.
- 75-kvar capacitors at busses T2, T8, T24, T44, T56.
- 100-kvar capacitors at bus T38.
- 112.5-kvar capacitors at bus T20.
- 137.5-kvar capacitors at bus T52.

Before capacitor placement and at the peak moment, the apparent power input was 4.406 MVA, the reactive power input was 2.208 Mvar, and power loss was 135.908 kW. After placing capacitors and at the peak moment, the apparent power input was 3.861 MVA, the reactive power input was 0.811 Mvar, and power loss was 104.798 kW. After capacitor placement and at the peak moment, the apparent power input was reduced by 0.545 MVA (equal to 12.37%), the reactive power input by 1.397 Mvar (or 63.27%), and power loss by 31.11 kW (equal to 22.89%).

The total capacity of all the capacitors added to the network under study was 1412.5 kvar at the peak moment of the year. Capacitor placement increased the usable capacity of the network by 0.545 MVA (equal to 12.37%) at the peak moment of the year.

c) Replacing transformers

Zero transformers should be changed. This finding can be analyzed as follows:

There were 28 transformers in the feeder studied in this research. The loss of the transformers consists of copper and iron loss. At the peak moment of the year, the total loss of all the transformers was 31 kW, the total iron loss was 19 kW, and the total copper loss was 12 kW, which was obtained from subtracting iron loss from total loss. The total loss of all the transformers amounted to 21.71% of the total loss of the network. Iron loss was equal to 61.29% of the total loss of the transformers and 13.30% of the total loss of the network. Copper loss was equal to 38.70% of the total loss of the transformers and 8.40% of the total loss of the network.

Replacing dilapidated transformers will result in a decrease of 20% in the total loss of transformers. In other words, a reduction of 6.2 kW will bring the total loss of transformers to 24.8 kW. This means that the total loss of the network will reduce by 4.34%. Given that the benefit of loss reduction resulting from replacing dilapidated transformers will be $7960 per year, and that replacing all the transformers will cost $152633, the benefit to be obtained from replacing dilapidated transformers will be insignificant.

d) Replacing line conductors

Table 7 shows the results of replacing line conductors.

Table 7: Replacing line conductors

Item	Quantity
Loss after run	112.789 kW
Loss reduction	30.027 kW
Cost	$1752.752
Benefit	$2177.653
|OF|	$424.901

The total loss of lines was 111.816 kW, amounting to 78.29% of the total loss of the network at the peak moment.

Replacing the dilapidated conductors of a line reduces its resistance by 10%. This results in a corresponding decrease in the loss of the lines as loss is positively related to resistance. Thus, replacing all dilapidated conductors will lead to a reduction of around 7.83% in the total loss of the network. Loss will be reduced by 11.182 kW. The benefit to be obtained will be $9169 per year. Given that all the lines in the network are about 19 km in length, replacing all the conductors will be approximately $114000. This means that the benefit to be obtained from replacing dilapidated conductors will be insignificant.

e) Correcting loose connections

Loose connections should not be replaced. The analysis is as follows:

As mentioned earlier on, the resistance of a loose connection in the network under investigation was 0.0001 ohm. The resistance of the loose connections in a .480-km line was .0003 ohm. The resistance of a .480-km line was 0.11904 ohm. The resistance emanating from loose connections makes up 0.08% of the total resistance of the line. Fixing loose connections in a line will cost $1.406.

Loss is positively related to resistance. The loss resulting from loose connections constitutes 0.08% of the loss emanating from resistance. The loss caused by network lines makes up 78.29% of the total loss of the network. As a result, the loss induced by loose connections is equal to 0.06% of the total loss of the network. In other words, the total loss resulting from loose connections is about 85.69 watts, meaning that the profit obtained from reducing it will be around $70.26 per year. Given that the total number of loose connections in the network under discussion was considered to be 2514, we will need $3535 to fix all those connections. It can be seen that the benefit to be obtained from fixing loose connections seems trivial when compared with the costs involved.

f) All the methods applied simultaneously

Different capacitors were installed at different busses as follows:

- 12.5-kvar capacitors at busses T4, T42, T46.
- 25-kvar capacitors at busses T12, T22, T28, T36, T48.
- 37.5-kvar capacitors at busses T8, T16, T40, T52.

- 50-kvar capacitors at busses T20, T32, T38.
- 62.5-kvar capacitors at busses T14, T50.
- 75-kvar capacitors at busses T10, T26.
- 100-kvar capacitors at busses T2, T44.
- 112.5-kvar capacitors at bus T56.

The results of simultaneously applying all the methods are given in Table 8.

Table 8: All the methods applied simultaneously

Quantity	Item
Loss after run	108.054 kW
Loss reduction	34.762 kW
Cost	$15152.416
Benefit	$28502.485
|OF|	$13350.069
Cost of Fixing load imbalance	$1182.216
Cost of Placing capacitors	$13970.200

The results show that of all the five methods of reducing loss, only placing capacitors and fixing load imbalance seem cost-effective. More specifically, simultaneously applying all the methods reduces power loss by 20.11%, with the ratio of benefit to cost being 1881 to 1000. The total capacity of the capacitors added to the network was 1050 kvar.

Table 9 and Table 10 summarize the benefit-cost ratio and percentage of loss reduction, respectively. The best method of loss reduction will be fixing load imbalance if the decision is based on the benefit-cost ratio. However, if the percentage of loss reduction forms the basis of our decision, placing capacitors will turn out to be the best method.

Table 9: benefit-cost ratio

Method	benefit-cost ratio
Fixing load imbalance	8.57
Placing capacitors	1.39
Replacing line conductors	1.24

Table 10: percentage of loss reduction

Method	percentage of loss reduction
fixing load imbalance	13.55
Placing capacitors	22.89
Replacing line conductors	21.02

6) Conclusion

This research used five ways of reducing power loss in a distribution network: fixing load imbalance, placing capacitors, replacing dilapidated transformers, replacing dilapidated conductors, and fixing loose connections. These methods were applied both separately and collectively in order to determine how effective each is on power loss. In addition, account was taken of operational costs. We also determined the optimum location and capacity of each capacitor. A new model was proposed for fixing load imbalance. The results show the best methods of loss reduction to be fixing load imbalance and placing capacitors. The former is advised if the benefit-cost ratio forms the basis of our decision. However, considering the percentage of loss reduction makes the latter the better choice.

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