LOSS REDUCTION IN A DISTRIBUTION SYSTEM BY CONSIDERING INTEREST RATE

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Abstract:

This paper is a report on a study which attempted to explore the effect of the rate of interest on the invested capital for the period under study, or interest rate (IR) for short, on loss reduction in an actual distribution network in Iran (Qazvin Power Distribution Company). For this purpose, five methods of loss reduction were compared in terms of the degree of loss reduction and cost-effectiveness: load imbalance adjustment, capacitor placement, and replacement of inappropriate transformers, dilapidated conductors, and weak connections. The objective function was performed both by and without considering IR. It was found that if IR is considered, more reduction will be realized and findings will be more realistic. This indicates that loss reduction is more cost-effective in the countries where IR is higher than in other countries. The model presented in this paper can help power utilities decide whether or not to invest in loss reduction. This work was fully funded by the Qazvin Electric Distribution Company under the contract number 420.

1 Introduction

Energy preservation is immeasurably important when considering environmental issues, the expensiveness of fossil fuels, formation of private power utilities, and the costs and time associated with developing power plants. National governments have made a lot of investment into reducing loss of electrical energy, with the most attention being paid to the distribution level due to the high amount of loss at this level. Clearly, loss implies that a considerable amount of energy generated for sale is wasted. This imposes many charges on power utilities and also the industry.

Loss regarded as a function of various factors[1] summarizes the main components 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 and

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- Ohmic loss in leakage currents of shunt equipment, such as insulators and arrestors.

A broad range of methods have been tried over the past few decades for reducing loss. Ref. [1] presents a list of these methods at the distribution level:

- Reconductoring in primary and secondary feeders;
- Reconfiguring feeders;
- Using high efficiency distribution transformers;
- Reducing secondary network length by adding and optimally placing distribution transformers;
- Using distributed generation[2];
- Placing subtransmission substations near load centers;
- Load balancing;
- Improving load factor and
- Improving voltage profile[3].

Among the causes of loss there are load imbalance, reactive power, dilapidated transformers, dilapidated conductors, and weak connections. By adjusting load imbalance, loss in the lines and transformers will be decreased. A capacitor which is optimally placed in a distribution network improves power factor and reduces reactive power. By replacing overworked and dilapidated transformers copper and iron loss are reduced. The cables and conductors which have dilapidated due to weather conditions should be replaced as their increased resistance results in the loss of power. And finally, line resistance and power loss are reduced by correcting the connections weakened with the passage of time.

An important factor influencing the effectiveness of the method used to reduce loss is network typology. Only at a great cost does a method sometimes reduce loss.. Thus, the best method of reducing loss is one that is cost-effective for the distribution system under study.

A review of previous works on loss reduction follows.

Ref. [4] made an attempt to reduce loss via removing load imbalance. The loss reduction method employed by [5] was balancing transformer load, taking account of the cost recovery period.

Another method used in loss reduction has been capacitor placement. For example, [6] evolutionary fuzzy programming algorithm and dynamic information structure were used in order to determine the optimum location for capacitors in a 69-bus radial distribution system. Ref. [1] used Genetic Algorithm (GA) for capacitor placement in a 69-bus system. Ref. [7] placed capacitors using the Particle Swarm Optimization (PSO) algorithm. The operating costs associated with capacitor placement were taken into consideration in [8] and [9].

Ref. [10] found that the loss in a transformer is reduced if the transformer works with about half of the nominal load and if harmonics filters are installed.

Ref. [11] proposed an algorithm for deciding on the optimum conductor for a radial distribution network and for reducing the network loss by means of a new load flow.

[12] studied the effect of fixing weak connections on loss reduction in Hormozgan power network in Iran considering the operating costs involved.

Some authors have tried a mixture of different reduction methods. As for instance, [13] used a reconfiguration and capacitor control in a 119-bus system. Network reconfiguration and capacitor placement were jointly used by [14]. [15] attempted to reduce loss through capacitor placement and voltage adjustment.

Each of the papers reviewed used only one or two methods for reducing loss. However, the present research prioritized five ways of reducing power loss in an actual feeder from the point of view of operating costs, i.e., adjusting load balance, placing and sizing capacitors, replacing dilapidated conductors and transformers, and correcting loose connections.

More specifically, this study attempted to reduce power loss in the 20-kV distribution network of Sharif-Abad, which is a part of Qazvin Power Distribution Company in Iran, considering the rate of interest on the invested capital for the period under study, or interest rate (IR) for short. This was also compared with the case in which IR was not an issue. The purpose of the objective function was to minimize the costs associated with load imbalance adjustment, capacitor placement, replacement of inappropriate transformers, dilapidated conductors, and weak connections using the Genetic Algorithm. Another consideration was maximizing the financial gain from power loss reduction.

It is worth noting at this point that a similar research was performed in [16]. They considered the loss factor in the feeder under investigation to be 0.52. However, the loss factor in the present research was considered to be 0.4047 because we measured both peak power loss and the energy loss in the year at issue. Another difference between the two studies is the consideration of IR.

2 Model formulation

Balanced transformer loads have been accomplished by using different methods. These methods attempt to bring the currents associated with the phases of each load closer to the average current [4, 5].
An effective method for reducing loss in a network is an optimal capacitor placement, which is performed in numerical, analytical, heuristic, or, more recently, intelligent methods [1, 6-9]
The loss of distribution transformers can be reduced in several ways, i.e., by using better quality materials, half loading, and harmonic filters [10], to name only a few.
Two efficient ways of reducing the loss of lines can be achieved by using appropriate conductors [11] and fixing weak connections [12].

2.1 Fixing load imbalance

As stated in [16], fixing load imbalance requires the current of each phase to be close to the average current of the three phases.
Load imbalance was adjusted as follows:

- The percentage of imbalance was determined for each phase (Eq. (1)).
- A certain percentage (from 0 to 100) was randomly allotted to each load through the use of GA.
- The cost of imbalance adjustment 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 adjustment for each load is equal to the sum of the costs associated with imbalance adjustment for the three phases.
- The total cost of imbalance adjustment is equal to the sum of the costs associated with imbalance adjustment for all the loads in the feeder under investigation (Eq.(2)).

$$a_{old} = \frac{I_p - I_{ave}}{I_{ave}}, \tag{1}$$

where I_p (A) is the phase current, and I_{ave} (A) is the average of the three phase currents.

$$C_{imbalance} = A\sum_{i=1}^{n} \ln\left(\frac{a_{old-R-i} \times a_{old-S-i} \times a_{old-T-i}}{a_{new-i}^{3}}\right) \tag{2}$$

where $C_{imbalance}$: the cost (\$) of adjusting imbalance, A is a constant set at \$70 according to our empirical work, $a_{old-p-i}$ is the old percentage of load imbalance for the pth phase of the ith load and a_{new-i} is the new percentage of load imbalance for the ith load.
It should be noted that the cost of reducing load imbalance from 60% to 50% is less than the cost associated with decreasing imbalance from 30% to 20% (Figure 1).

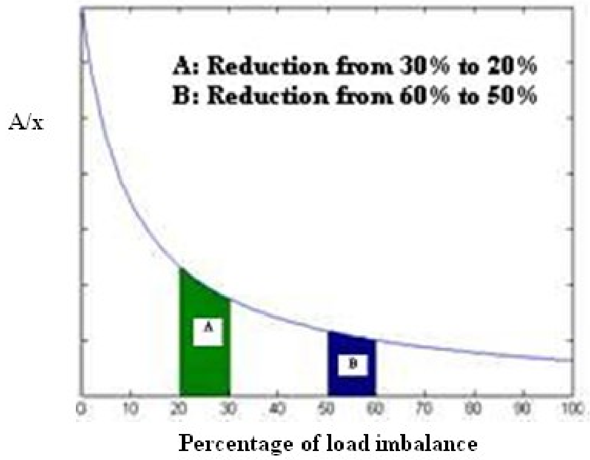

Figure 1. The A/x diagram.

Figure *2* is the flowchart referring to fixing load imbalance.

2.2 Capacitor placement

Capacitors were placed bearing in mind that [16]:

- Capacitors were only placed where loads occured.
- Loads were adjusted and allotted before assembling the capacitor.
- Capacitors for up to 12.5-kvar ratings were used. 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 referring to capacitor placement were added up to the objective function.

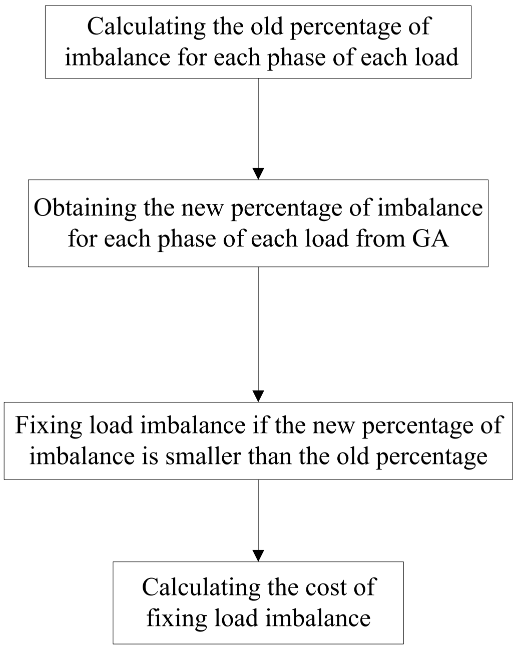

Figure 2. The flowchart of fixing load imbalance.

- Fixed costs in this research 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. (3)).

$$Q_c = Q_1 - Q_2 = P(\tan\phi_1 - \tan\phi_2), \qquad (3)$$

where:

- Q_c: is the capacity of the installed capacitor (kvar);
- Q_1: reactive power before installing the capacitor (kvar);
- Q_2: reactive power after installing the capacitor (kvar);
- P: active power (kW);
- ϕ_1: phase angle between the current and voltage before the installing capacitor;
- ϕ_2: phase angle between the current and voltage after the installing capacitor;

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

The cost of capacitor placement for the entire network is calculated via Eq.(4). Also, Eq.(5). and Eq. (6) calculate the cost of capacitor placement for each bus and the variable cost of placing capacitors for each bus, respectively.

$$C_{cap} = \sum_{i=1}^{i=n} C_{cap-i}, \qquad (4)$$

where

- C_{cap}: the cost of capacitor placement ($);
- C_{cap-i}: cost of placing capacitors on the i^th bus ($);

$$C_{cap-i} = C_{cap-fixd-i} + C_{cap-\mathrm{var}iable-i} \qquad (5)$$

where

$C_{cap-fixd-i}$: fixed cost of placing capacitors on the i^th bus ($);

$C_{cap-\mathrm{var}iable-i}$: variable cost of placing capacitors on the i^th bus ($);

$$C_{cap-\mathrm{var}iable} = n_{cap} \times p_{cap} \qquad (6)$$

Where

- n_{cap}: number of capacitors on the i^th bus;
- p_{cap}: price of each capacitor ($/unit).

2.3 Replacing dilapidated transformers

Following [16], we replaced the dilapidated transformers in the manner described below:

- The transformers used in the feeder under study had the following apparent power rating values: 25, 50, 100, 200, 250, 315, 500, and 630 kVA.
- A gene was considered for each transformer.
- If a transformer is replaced, its copper and iron losses decrease by 20%, as reported by [17].
- Lastly, the costs involved in replacing all transformers (obtained from Eq. (7)) were added up so that the total cost of transformer replacement was known.

$$C_{trans} = \sum_{j=1}^{8} C_{trans-type-j} \times n_{type-j} \quad (7)$$

where:

- $C_{trans-type-i}$: the cost of replacing type-j transformers (Table 5);
- n_{type-i}: the number of type-j transformers which need to be replaced.

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

2.4 Replacing dilapidated lines

Dilapidated lines were replaced on the basis of the following [16]:

- A gene was considered for each line.
- If a line is replaced, its resistance decreases by 10%, as stipulated in [17].
- Finally, the costs associated with replacing all dilapidated lines were added up in order to obtain the total cost of line replacement.
-

$$C_{Line} = \sum (p_{line-i} \times l_i) \quad (8)$$

- p_{line-i}: the price of one meter of the i^th^ line;
- l_i: the length of the i^th^ line to be replaced.

The cost of conductor replacement is the sum of all the expenses associated with replacing the conductors, as determined by GA (Eq.(10)).

2.5 Correcting weak connections

As in [16], weak connections in the network were corrected in the following way:

- The length of the lines connecting buses was calculated by using 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 is true about single-wire lines only. For three-wire lines, the number should be multiplied by three.
- If a weak connection is corrected, line resistance decreases by 0.001 ohms, according to [17].
- Lastly, to calculate the total cost of correcting weak connections, the operational costs related to correcting each connection was multiplied by the total number of connections (Eq. (9)).

$$C_{connection} = n_{connection} \times p_{connection} \quad (9)$$

Where:

- $C_{connection}$: the cost of correcting weak connections ($);
- $n_{connection}$: the total number of weak connections;
- $p_{connection}$: the cost of fixing each weak connection ($/unit).

2.6 The benefit obtained from reducing power loss

The benefit obtained from reducing power loss is calculated through Eq. (10) given in [16].

$$B_{loss\_reduction} = (P_{loss-after} - P_{loss-before}) \times H_{Total} \times LSF \times p_{energe} \quad (10)$$

where:

- $B_{loss-reduction}$: the benefit resulting from loss reduction ($);
- $P_{loss-after}$: loss after the application of the methods (kW);
- $P_{loss-before}$: loss before the application of the methods (kW);
- H_{Total}: total hours period under study
- LSF: the loss factor, which is equal to energy loss (kWh) in a given period (8760 h in this research) divided by the product of the period and power loss at peak load (kW);
- p_{energe}: the price of electrical energy sold in the Iranian market ($/unit).

2.7 Objective Function

The objective function was defined using Eq. (11) below:

$$OF_1 = \overbrace{C_{imbalance} + C_{cap} + C_{trans} + C_{line} + C_{connection}}^{a} + \overbrace{B_{loss\_reduction}}^{b} = a + b \qquad (11)$$

where:

- OF_1: objective function without considering IR ($);
- $C_{imbalance}$: the cost of adjusting imbalance ($);
- C_{cap} : the cost of capacitor placement ($);
- C_{trans} : the cost of transformer replacement ($);
- C_{line} : the cost of conductor replacement ($);
- $C_{connection}$: the cost of correcting weak connections ($);
- $B_{loss-reduction}$: the benefit resulting from reducing power loss ($);
- a : total costs;
- b : total benefits.

The flowchart of the OF is displayed in Figure *3*.

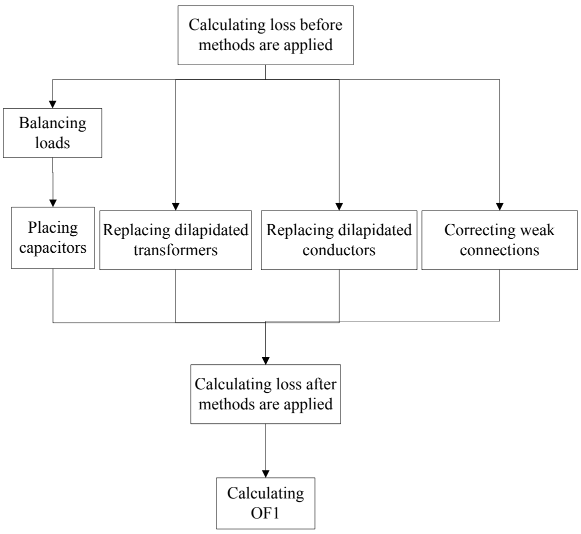

Figure 3. The flowchart of the OF_1 for each iteration.

3 New Method

This paper sets out to consider IR in OF_1. Given the fact that loss reduction requires the payment be made in advance of implementing the pertinent methods and also because the possible benefits will be seen after a year or so, IR comes to be particularly important. Taking IR into consideration involves changing OF_1 in the following way. The resultant objective function will be called OF_2.

3.1 Objective Function considering IR

Considering IR in OF_1 (=A), we get OF_2 (=B) as described below:

A at the beginning of the 1st month: $B_0 = a_0$.
A at the end of the 1st month: $B_1 = K \times B_0 + H$.
A at the end of the 2nd month: $B_2 = K \times B_1 + H$.
A at the end of the 3rd month: $B_3 = K \times B_2 + H$.
A at the end of the 4th month: $B_4 = K \times B_3 + H$.
(…)
A at the end of the nth month: $B_n = K \times B_{(n-1)} + H$.

K and H in the relations above are defined as follows:

$K = (1 + \dfrac{\alpha}{n})$ and $H = \dfrac{b}{n}$, where:

- α : IR in the period under study,
- b : benefit resulting from loss reduction in the period under study,
- n : the period under study (in months),

In order to calculate OF_2 at the end of the nth month, we can go through the following steps:

$$B_0 = a_0$$
$$B_1 = K \times a_0 + H$$
$$B_2 = K^2 \times a_0 + K \times H + H = K^2 \times a_0 + H \times (K+1)$$
$$B_3 = K^3 \times a_0 + K^2 \times H + K \times H + H = K^3 \times a_0 + H \times (K^2 + K + 1)$$
$$B_4 = K^4 \times a_0 + K^3 \times H + K^2 \times H + K \times H + H = K^4 \times a_0 + H \times (K^3 + K^2 + K + 1)$$
(…)

$$B_n = K^n \times a_0 + K^{n-1} \times H + ... + K^3 \times H + K^2 \times H + K \times H + H = K^n \times a_0 + H \times (K^{n-1} + ... + K^3 + K^2 + K + 1)$$

Eq. (12) can be rewritten as Eq. (13)below:

$$B_n = K^n \times a_0 + H \times (\frac{K^n - 1}{K - 1}) . \qquad (13)$$

If IR is considered zero, $K = 1$. Thus, Eq. (12) will be equal to Eq. (11). In other words, $(OF_2 = B) = (OF_1 = A)$.

4 Simulation

4.1 Case study

The distribution system used in this research was the 20-kV Feeder of Sharif-Abad in northwestern Iran. The schematic represenation of this feeder is given in Figure 4. Figure 5 expands the area marked in Figure 4.

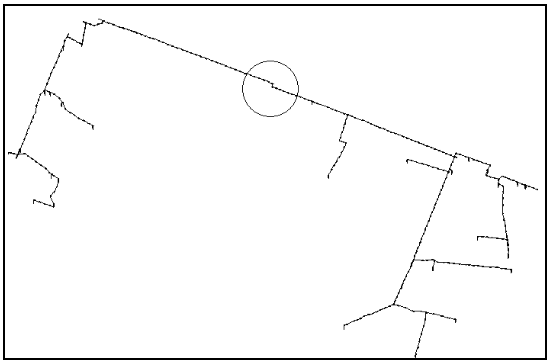

Figure 4. The schematic representation of Sharif-Abad Feeder.

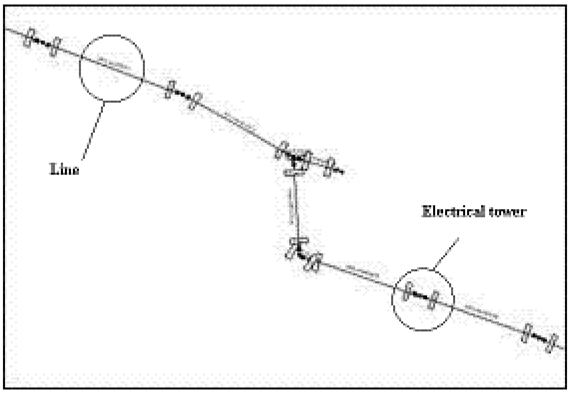

Figure 5. The enlargement of the area marked in Figure 4.

Table 1 presents different levels of apparent power as used in the network under investigation and the number of transformers associated with each level. There are nine agricultural transformers in this feeder.

Table 2 gives the number of transformers associated with different levels of apparent power used in the network. The specifications of this feeder are given in Table 3 and Table 4 below. Table 5 summarizes the operating costs of the methods applied.

Table 1. Levels of apparent power and the number of associated transformers

Apparent power (kVA)	Number of associated transformers
25	1
50	1
100	8
200	6
250	6
315	4
500	1
630	1

Table 2. The number of agricultural transformers associated with levels of apparent power

Level of apparent power (kVA)	Number of associated transformers
100	6
200	3

Table 3. A sample of the length of line between every two terminals

Terminals i-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 4. 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

Table 5. Operational costs

Equipment and services	Cost
Capacitor 12.5 kvar	136.550 ($/unit)
Fixed cost 1	100 ($/unit)
Fixed cost 2	200 ($/unit)
Fixed cost 3	300 ($/unit)
Type-1 trans (25 kVA)	2266.938 ($/unit)
Type-2 trans (50 kVA)	2707.938 ($/unit)
Type-3 trans (100 kVA)	3688.177 ($/unit)
Type-4 trans (200 kVA)	5602.810 ($/unit)
Type-5 trans (250 kVA)	5792.808 ($/unit)
Type-6 trans (315 kVA)	6863.947 ($/unit)
Type-7 trans (500 kVA)	10352.565 ($/unit)
Type-8 trans (630 kVA)	11970.326 ($/unit)
Conductor type1	4.092 ($/kg)
Conductor type2	4.246 ($/kg)
Energy	0.180 ($/kWh)

4.2 Software

DIgSILENT Power Factory 13.2 was used to develop the proposed algorithm for the OF and to analyze the system. As an advanced software application for simultaneous analysis of power networks and control systems, DIgSILENT can calculate load flow, short-circuit level, active losses of the network, and the network parameters. The main feature of the application is DPL (DIgSILENT Programming Language), which makes the proposed method very simple for application.. The OF was optimized by using GA on MATLAB R2008a Software. A text file was used to connect the two applications.

4.3 Optimization technique

For the sake of optimization, first a population is defined. This initial population is formed by binary accidental quantification of chromosomes. The produced population is then subjected to the OF so as to obtain the fitness of chromosomes. Eq. (14) shows the relationship between the OF and fitness.

$$Fitness = \frac{1}{OF} \tag{14}$$

Next, chromosomes need to be selected from the current population for reproduction. For this purpose, two parent chromosomes are chosen on the basis of their fitness values, which are used at a later stage by the genetic operators of crossover and mutation to produce two offsprings for the new population. In crossover, genetic information between pairs, or larger groups, of individuals is exchanged. This research used two-point crossover for recombination. If only the crossover operator is used to produce an offspring, a 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 offsprings will have this same value at this position. To overcome this problem, we need mutation, a process which attempts to change some of the genes randomly. The present work used both operators to ensure global optimization [18].

4.4 Proposed algorithm

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

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

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

1) DIgSILENT writes the zero in the text file to flag the beginning of the initial calculation. Detecting this flag, GA will not begin the associated program.
2) DIgSILENT writes the matrix $\begin{bmatrix} 1 \\ n_{\mathrm{var}\,s} \\ n_{\mathrm{var}\,s-imbalance} \\ n_{\mathrm{var}\,s-cap} \\ population\_size \\ Generation \end{bmatrix}$ in the text file. The first

row is the flag which shows the program must begin its operation. When the flag is set to 1, GA must run. $n_{\mathrm{var}\,s}$, $n_{\mathrm{var}\,s-imbalance}$, and $n_{\mathrm{var}\,s-cap}$,respectively and identify the total number of the genes within the chromosome, those related to load imbalance, and those associated with the capacitors.

3) GA writes the matrix $[2 \quad B_1...B_n\, C_1...C_n \quad T_1...T_n\, L_1...L_m \quad X_1...X_k]$ in the text file. In this matrix, $B_1,...,B_n$ are the new percentages of imbalance for each load , $C_1,...,C_n$ are the number of 12.5-kvar ratings of the capacitors for each load, $T_1,...,T_n$ are the values of 0 or 1 referring to each transformer, $L_1,...,L_m$ are the values of 0 or 1 associated with 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 commences the operation and calculates the OF using the chromosome given in that file. The application, is then inserted into 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 has not been reached, the process described above reverts to Stage 3. Otherwise, the process goes on to Stage 6 below.
6) The GA is finished, so it inserts Flag 4 into the text file, denoting 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

In this research, the loss factor was considered to be 0.4047, and the following items were calculated with regard to attendant costs:

1) Adjusting load imbalance
2) Placing capacitors
3) Replacing transformers
4) Replacing line conductors
5) Correcting weak connections
6) All the above carried out together.

It is worth noting that IR was considered to be 24% and the period under study was regarded as being 12 months long (n = 12).

5.1 Adjusting load imbalance

Table 6 summarizes the results of adjusting load imbalance in transformers.

Table 6. Fixing load imbalance

Operation	Running OF without considering IR	Running OF considering IR
Loss reduction	13.140 kW	19.504 kW
Cost=a_0	\$1234.419	\$1892.811
Benefit=b	\$8453.307	\$12446.355
|OF|	\$7218.888	\$11510.427

The results from running OF_1 can be analyzed as follows:
Power loss was 129.389 kW after load imbalance had been corrected, indicating a drop of 13.14 kW, which equals 10.16% of the total loss of the network. The cost of balancing all the loads was obtained from Eq. (2). The quantity of phase current R was 1.5 times as large as that of the average current. The quantities of phase currents S and T were respectively 0.8 and 0.7 times of the average current. The 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, by reducing the surplus of phase current R to 30%, we can reduce the deficit of phase currents S and T to 10% and 20%, respectively, at a cost of \$112.7. The loss reduction thus obtained will be 21 MWh, and the resultant benefit will be \$3700 a year.
A similar analysis can be provided for the results from running OF_2. A comparison of the OF_1 and OF_2 results shows that the degree of loss reduction in the case of OF_2 is 6.364 kW higher than in the case of OF_1. However, load balancing was costlier with OF_2 than with OF_1: there is a difference of \$658.392. The benefit obtained in OF_2 was \$3993.048 more than in OF_1. OF_2 was larger than OF_1 by \$4291.539. In general, OF_2 was better than OF_1. It follows that in Iran, and every other country where IR is high, OF_2 seems a better alternative than OF_1.

5.2 Placing capacitors

Unless load imbalance had been adjusted, capacitors could not be placed. Hence, loss should have a different amount before capacitor placement than before the deployment of any of the other methods. The results of allocating capacitors in the network are given in Table 7.

Table 7. Capacitor allocation

Operation	Running OF without considering IR	Running OF by considering IR
Loss reduction	22.936 kW	19.85 kW
Cost=a_0	\$12677.8	\$10975.750
Benefit=b	\$14755.802	\$12667.058
|OF|	\$2078.002	\$237.784

With OF_1, different capacitors were placed at different busses as follows:

- 12.5-kvar capacitors at busses T18, T28, T36.
- 25-kvar capacitors at busses T2, T4, T10, T20, T50.
- 37.5-kvar capacitors at busses T26, T30, T40, T46, T48, T54.
- 50-kvar capacitors at bus T22.
- 62.5-kvar capacitors at bus T14.
- 75-kvar capacitors at busses T38, T44, T56.
- 87.5-kvar capacitors at bus T24.
- 137.5-kvar capacitors at bus T52.

In the case of OF_2, capacitor placement at different busses was as follows:

- 12.5-kvar capacitors at busses T18, T42, T54.
- 25-kvar capacitors at busses T4, T24, T28, T46, T48.
- 37.5-kvar capacitors at busses T10, T12, T14, T26, T30.
- 50-kvar capacitors at bus T2, T20, T22, T34, T50.
- 62.5-kvar capacitors at bus T40.
- 75-kvar capacitors at busses T38, T56.

An analysis of running OF_1 is given below:
Before capacitor installation and at the peak moment of the year (i.e., the moment when maximum energy is generated), the apparent power input was 4368.262 kVA, the reactive power input was 2143.851 kvar, and power loss was 135.719 kW. After placing capacitors and at the annual peak moment, the apparent power input was 3973.889 kVA, the reactive power input was 1216.810 kvar, and power loss was 112.783 kW. This shows that the apparent power input was reduced by 394.373 kVA (equal to 9.03%), the reactive power input by 927.041 kvar (or 43.24%), and power loss by 22.936 kW (i.e., 16.90%).
The total capacity of all the capacitors added to the network under investigation was 950 kvar at the peak moment of the year. Capacitor installation increased the usable capacity of the network by 394.373 kVA (equal to 9.03%) at the peak moment of the year.
The analysis of the results from running OF_2 is similar to the one provided for OF_1. A comparison of the results for OF_1 and OF_2 shows that the degree of loss reduction in the case of OF_2 is 3.86 kW lower than in the case of OF_1. Capacitor placement was costlier with OF_1 than with OF_2: a difference of \$1702.05. The benefit obtained in OF_2 was \$2088.744 less than in OF_1. OF_2 was smaller than OF_1 by \$1840.218. This entire analysis means that OF_1 was better than OF_2, with the two main reasons being the high cost of capacitor placement and high IR in Iran.

5.3 Replacing transformers

The results from running both OF_1 and OF_2 for transformer replacement revealed that no replacement should take place. This finding can be explained as follows:
There were 28 transformers in the feeder studied in this research. The energy loss of the transformers is attributed to copper and iron loss. At the peak moment of the year, the total loss of all the transformers was 31 kW, with the total iron loss being 19 kW, and the total copper loss being 12 kW. The total loss of transformers constituted 54.82% of the total loss of the network. It should be noted at this point that the total loss of a transformer is divided up into two parts: iron loss and copper loss. The calculated iron loss and copper loss, respectively constituted 60.29% and 39.71% of the total loss of transformers. Also, 33.05% of the total loss of the network resulted from transformer iron losses, whereas 21.77% resulted from transformer copper losses.
By replacing dilapidated transformers, the total loss of transformers is reduced by 20%. That is to say, a

reduction of 55.4 MWh will bring the total loss of transformers to 221.6 MWh. It follows that the overall loss of the network will be reduced by 10.96%. Given that the benefit of loss reduction resulting from replacing dilapidated transformers will be $7523 a year, and that replacement of all the transformers will cost $152633, the benefit to be obtained by replacing dilapidated transformers will not be significant.

5.4 Replacing line conductors

An analysis of running OF_1 follows:
The total loss of lines was 228.30 MWh, equaling 45.18% of the total loss of the network. By replacing the dilapidated conductors of a line, its resistance was decreased by 10%. This correspondingly reduces the loss of the lines as loss is positively related to resistance. Thus, replacing all dilapidated conductors will result in a reduction of about 4.52% in the overall loss of the network. Loss will be reduced by 22.83 MWh. The benefit to be obtained will be $4109.4 a year. The cost of replacing all the conductors will be approximately $114000 given that all the lines in the network are about 19 km in length. In consequence, the benefit to be obtained by replacing dilapidated conductors will be insignificant. Table 8 summarizes the results of line conductor replacement.
The results from running OF_2 can be analyzed in a way similar to OF_1 results. Comparing the two, we can see that the degree of loss reduction in the case of OF_2 is 0.009 kW lower than in the case of OF_1. Line conductor replacement was costlier with OF_1 than with OF_2: a difference of $16.863. The benefit obtained in OF_2 was $7.381 less than in OF_1. OF_2 was smaller than OF_1 by $9.081. All these calculations indicate that the two OFs are minimally different, perhaps because dilapidated conductors were replaced at a low cost. In other words, IR was insignificantly effective on OF_1

Table 8. Replacing line conductors

Operation	Running OF without considering IR	Running OF by considering IR
Loss reduction	0.295 kW	0.286 kW
Cost=a_0	$166.089	$149.226
Benefit=b	$189.787	$182.406
|OF|	$23.698	$14.617

5.5 Correcting weak connections

On the basis of the results obtained from running both OFs in the case of weak connection correction, it was discovered that no connection should be corrected. The explanation follows:
As mentioned above, the resistance of a weak connection in the network under study was 0.0001 ohm. The resistance of the weak connections in a 0.480-km line was 0.0003 ohm. The resistance of a 0.480-km line was found to be 0.11904 ohm. The resistance emanating from weak connections is equal to 0.08% of the total resistance of the line. Fixing weak connections in a line will cost $1.406.
Loss is positively related to resistance. The loss emanating from weak connections constitutes 0.08% of the loss caused by resistance. The loss resulting from network lines makes up 45.18% of the overall loss of the network. Therefore, the loss induced by weak connections is equal to 0.036% of the total loss of the network. That is, the total loss resulting from weak connections is around 182 kWh, meaning that the profit obtained from reducing it will be around $32.760 a year. Given that the total number of weak connections in the network under discussion was 2514, $3534 will be needed to fix all those connections. The benefit to be obtained from fixing weak connections seems trivial in comparison with the costs involved.

5.6 All the methods applied simultaneously

With OF_1, different capacitors were placed at different busses as follows:

- 12.5-kvar capacitors at busses T4, T54.
- 37.5-kvar capacitors at busses T20, T38, T40, T48.
- 50-kvar capacitors at busses T8, T16, T26, T30, T44.
- 62.5-kvar capacitors at busses T14, T56.
- 75-kvar capacitors at busses T32, T50.
- 100-kvar capacitors at bus T10.
- 50-kvar capacitors at busses T8, T16, T26, T30, T44.
- 112.5-kvar capacitors at bus T46.
- 137.5-kvar capacitors at bus T52.

In the case of OF_2, capacitor placement at different busses was as follows:

- 12.5-kvar capacitors at busses T8, T12, T28.
- 25-kvar capacitors at busses T38, T50, T54.

- 37.5-kvar capacitors at busses T2, T22, T52.
- 50-kvar capacitors at busses T24, T44.
- 75-kvar capacitors at buss T26.

Table 9 presents the results of simultaneous application of all the methods.

Table 9. All the methods applied simultaneously

Operation	Running OF without considering IR	Running OF by considering IR
Loss reduction	25.795 kW	28.677kW
Cost=a_0	$14008.043	$7233.835
Benefit=b	$16460.424	$18299.505
|OF|	$2452.381	$11278.632
Cost of Fixing load imbalance	$437.843	$1664.235
Cost of Placing capacitors	$13570.200	$5569.6

Below is an analysis of running OF_1:
Of all the five methods of loss reduction, only placing capacitors and fixing load imbalance seem to be cost-effective. More specifically, by simultaneously applying all the methods, the power loss is reduced by 18.10%, with the ratio of benefit to cost being 47 to 40. The total capacity of the capacitors added to the network was 1050 kvar.
For OF_2, a similar analysis can be provided. A comparison between the results obtained from running the two OFs shows that the degree of loss reduction in the case of OF_2 is 2.882 kW higher than in the case of OF_1. OF_1 was costlier than OF_2 to run by $6774.208. The benefit obtained in OF_2 was $1839.081 more than in OF_1. OF_2 was larger than OF_1 by $8826.251.
In the case of OF_2, it can be concluded that the application of the three methods simultaneously results in a more significant reduction of loss at a lower cost.
In general, OF_2 proved to outstrip OF_1. From another perspective, the high IR in countries like Iran makes OF_2 a better alternative than OF_1.

6 Conclusion

This study investigated the effect of interest rate on the investment in loss reduction in the power industry. For this purpose, five methods of loss reduction were applied to an actual distribution network: adjusting load imbalance, placing capacitors, replacing dilapidated transformers, replacing dilapidated conductors, and correcting weak connections. These methods were applied by and without considering IR. The results show that when considering IR more realistic results are produced. The results indicate that loss reduction is particularly cost-effective in the countries where IR is high. This work was limited by the fact that only the five methods discussed were applicable to the network under study. Thus, it seems advisable to evaluate some other methods such as reconfiguration and distributed generation resources installation. It would also be a good idea to consider inflation rate in the proposed model. Finally, when the model is put into operation, load imbalance adjustment should always be performed before capacitor placement. No particular order is needed for other methods of loss reduction.

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