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ORIGINAL SCIENTIFIC PAPER

A cost-effective analysis of the power-loss reduction methods in an actual distribution network

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Abstract. The paper reports on a study in which the power loss, energy loss, and loss factor were measured in an actual distribution network in Iran (Qazvin Power Distribution Company) by using an innovative method of load estimation before evaluating five ways of approaching the problem from the point of view of operating costs. The objective function was to minimize the costs. adjusting the load imbalance, optimall placing capacitors, and removing inappropriate transformers, dilapidated conductors, and weak connections. Another consideration was to maximize the financial gain from the power-loss reduction. The results showed that the method proposed for the estimating load was appropriate because the general pattern of the load curve was similar to the pattern obtained from the actual measurements. Another finding was that adding capacitors and adjusting the load imbalance turned out to be the most efficient and cost-effective ways of reducing the loss concerning the facilities available in the network under study. This work was fully funded by the Qazvin Electrical Distribution Utility under contract number 420.

Keywords: Loss reduction, Load estimation, Load-imbalance adjustment, Capacitor placement, Inappropriate transformers.

Analiza metod za zmanjšanje izgube moči distribucijskega omrežja z upoštevanjem finančnih virov

Ta dokument je poročilo raziskave, ki je merila izgubo moči, izgubo energije in dejavnik izgube distribucijskega omrežja v Iranu (Qazvin Power Distribution Company). Merjenje je potekalo z inovativno metodo ocenjevanja obremenitve omrežja pred ocenjevanjem petih načinov reševanja problema z vidika operativnih stroškov. Namen raziskave je bil zmanjšanje stroškov, povezanih s prilagajanjem neenakomerne obremenitve, optimalno postavitvijo kondenzatorjev, odstranitvijo neprimernih transformatorjev, razpadajočih vodov in šibkih povezav. Drugi namen je bil maksimalno povečati finančni dobiček z zmanjšanjem izgube energije. Rezultati raziskave so pokazali, da je predlagana metoda za predvidevanje obremenitve omrežja primerna, saj je splošni vzorec krivulje obremenitve podoben vzorcu, pridobljenemu z dejanskimi meritvami. Prav tako je raziskava pokazala, da sta dodajanje kondenzatorjev in uravnavanje neenakomerne obremenitve najučinkovitejša in stroškovno primerna načina za zmanjšanje izgube energije glede na opremo, ki je bila uporabljena v omrežju v času raziskave. To raziskavo je v celoti financiralo podjetje Qazvin Electrical Distribution Company na podlagi pogodbe številka 420.

1 INTRODUCTION

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

The loss is a function of various factors. Ref. [1] summarizes the main components as follows:

- Ohmic loss in the conductors of the 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 the secondary feeders and customers
- Ohmic loss in the leakage currents of the shunt equipment, such as insulators and surge arrestors.

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

- Reconductoring in the primary and secondary feeders
- Reconfiguring the feeders
- Using high-efficiency distribution transformers

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- Reducing the secondary network length by adding and optimally placing distribution transformers
- Using distributed generation
- Placing subtransmission substations near the load centers
- Load balancing
- Improving the load factor
- Improving the voltage profile.

Among the causes of the loss are the load imbalance, reactive power, dilapidated transformers, dilapidated conductors, and weak connections. Adjusting the load imbalance decreases the loss in the lines and transformers. Optimal placing a capacitor in a distribution network improves the power factor and reduces the reactive power. Replacing the worn out and dilapidated transformers reduces the copper and iron loss. The cables and conductors which have dilapidated due to weather conditions should be replaced as their increased resistance results in the power loss. And finally, correcting the connections weakened over time will reduce the line resistance and the power loss.

An important factor afecting the effectiveness of the method used to reduce the loss is the network typology. Sometimes using a certain method reduces the loss, but only at a great cost. Thus, the best method of reducing the loss is the one that is cost-effective for the distribution system under study. A review of the previous works on the loss reduction follows.

Ref. [2] made an attempt to reduce the loss by removing the load imbalance. The loss-reduction method employed by ref. [3] was balancing the transformer load taking account of the recovery–period cost.

Another method to reduce the loss is capacitor placement. For example, ref. [4] used on evolutionary fuzzy programming algorithm and dynamic information structure in order to determine the optimal capacitor placement in a 69-bus radial distribution system. Ref. [1] used the Genetic Algorithm (GA) for capacitor placement in a 69-bus system. Ref. [5] placed capacitors by using the Particle Swarm Optimization (PSO) algorithm. The operating costs associated with the capacitor placement were taken into consideration in ref. [6] and ref. [7].

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

Ref. [9] proposed an algorithm for selecting on on optimal conductor for a radial distribution network and for reducing the network loss by means of a new load flow.

Ref. [10] studied the impact of fixing weak connections on the loss reduction in the Hormozgan power network in Iran considering the operating costs involved.

Some authors have tried a mixture of different reduction methods. Ref. [11] used network reconfiguration and capacitor control in a 119-bus system. Network reconfiguration and capacitor placement were jointly used by [12]. Ref. [13] attempted to reduce the loss through capacitor placement and voltage adjustment.

Each of the papers reviewed used only one two methods for reducing the loss.

In order to calculate the loss, we need to have access to the data about the substation loads in the period under study. However, as it is not practical to measure so many substation loads, we found it better to estimate the load instead. A quick review of the previous studies about the load estimation follows.

Ref. [14] proposed an algorithm for the load estimation which used as its input the data provided by automated meter reading (AMR). In another study [15], the load was estimated in a Brazilian radial distribution system using neural networks and fuzzy set techniques to generate standard load curves for classes of consumers based on their monthly energy consumption.

Study [16] proposed a new hybrid demand model for load estimation which works in two steps. In the first step, a state space model is used for estimating the loads at selected points in the network. In the second step, an artificial neural network (ANN) model is used for the short-term load forecasting so as to cope with the nonlinear behavior of the load. Load estimation using limited measurements was tried by [17]. The solution algorithm was implemented in an unbalanced, radial distribution network using a backward-forward sweep method.

However, the methods and approaches proposed in the above-mentioned studies require facilities which may not be available in all contexts. This prompted us to propose a new method for load estimation which we think can be implemented over a wider range of situations.

The authors of [18] prioritized five ways of reducing the power loss in an actual feeder from the point of view of operating costs: adjusting the load balance, placing and sizing the capacitors, replacing the dilapidated conductors and transformers, and correcting the loose connections. However, as they did not have any idea about the power loss at the peak load and the energy loss, they considered the loss factor to be 0.52 on the basis of the loss factor in the adjacent feeders. In the present research, however, the loss factor was obtained by measuring both the power loss at the peak load and the energy loss in the observed year.

The present work attempted to evaluate several ways of reducing the loss in the 20-kV distribution network of Sharif-Abad which is part of the Qazvin Power Distribution utility in Iran. The two important considerations were the operating costs involved and method efficiency. The methods which were subjected to evaluation were the load-imbalance adjustment, capacitor placement, and removal of the inappropriate transformers, dilapidated conductors, and weak connections. For this purpose, we first measured the power loss at the peak hour of the period spanning from October 2012 to September 2013. Then, the energy loss

for the period under the study was calculated using an innovative load-estimation method. Having the data for the power loss and energy loss, we obtained the loss factor of the network for the year-long period. The objective function used in the research was then minimized using the Genetic Algorithm (GA).
The present work is innovative in that an actual network was subjected to the following:

- Proposing a new method for estimating the load
- Measuring the power loss
- Calculating the energy loss
- Determining the loss factor
- Determining the efficiency of different methods of loss reduction

2 MODEL FORMULATION

Balancing the transformer loads is accomplished using different methods. These methods attempt to bring the currents associated with the phases of each load closer to the average current [2, 3].

An effective approach to reducing the loss in a network is optimal capacitor placement performed with numerical, analytical, heuristic, or, more recently, intelligent methods [1, 4-7].

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

Two efficient ways of reducing the line loss are using appropriate conductors [9] and fixing the weak connections [10].

As for the load estimation, a number of methods were considered earlier on: automated meter reading (AMR) [14], intelligent techniques [15, 16], and limited measurements [17].

2.1 *Fixing the load imbalance [18]*

Fixing the load imbalance requires that the current of each phase to be close to the average current of the three phases. The Load imbalance was adjusted in the following way:

- The percentage of the load imbalance was determined for each phase (Eq. (1)).
- A certain percentage (from 0 to 100) was randomly assigned to each load using GA.
- The cost of the 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 the imbalance adjustment for each load is equal to the sum of the costs associated with the imbalance adjustment for the three phases.
- The total cost of imbalance adjustment is equal to the sum of the costs associated with the imbalance adjustment for all the loads in the feeder under study (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 the imbalance adjustment ($)
- A is a constant set at $70 according to our empirical work.
- $a_{old-p-i}$ -is the old percentage of the load imbalance for the pth phase of the ith load
- a_{new-i} -is the new percentage of the load imbalance for the ith load

It should be noted that the cost of reducing the load imbalance from 60% to 50% is less than the cost. decreasing the imbalance of 30% to one of 20% (Fig. 1).

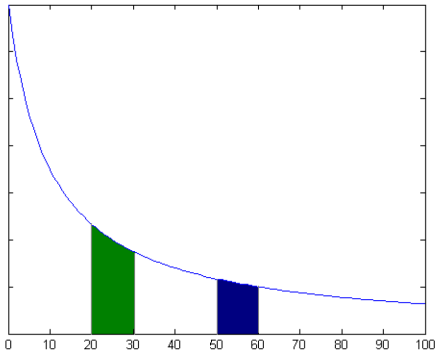

Figure 1. A/x diagram.

is a flowchart related to fixing the load imbalance.

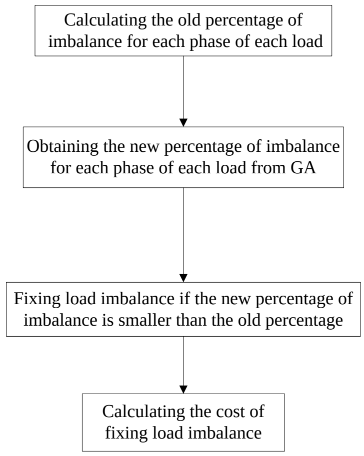

Figure 2. Flowchart of fixing the load imbalance.

2.2 *Capacitor placement [18]*

Capacitors were placed with the following in mind:

- Capacitors were only placed where the loads were.
- The loads were adjusted before capacitor placement.
- 12.5-kvar capacitors were used. The number of the capacitors was determined by GA.
- A gene was considered for each load.
- The total number of the capacitors multiplied by the price of each capacitor and the fixed costs related to the capacitor placement were added up in the objective function

- The 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 the steps was determined by the transformer with the highest capacity (Eq. (3)).

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

where:

- Q_c -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 installing the capacitor
- ϕ_2 -phase angle between the current and voltage after installing the capacitor

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

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 the maximum capacity of 222 kvar.

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

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

Where:

- C_{cap} -the cost of the capacitor placement ($)
- C_{cap-i} -cost of the placing capacitors on the ith bus ($)

$$C_{cap-i} = C_{cap-fixd-i} + C_{cap-variable-i} \quad (5)$$

Where:

- $C_{cap-fixd-i}$ -fixed cost of placing the capacitors on the ith bus ($)
- $C_{cap-variable-i}$ -variable cost of placing the capacitors on the ith bus ($)

$$C_{cap-variable} = n_{cap} \times p_{cap} \quad (6)$$

Where:

- n_{cap} -number of the capacitors on the ith bus
- p_{cap} -price of each capacitor ($/unit)

2.3 Replacing the dilapidated transformers [18]

The dilapidated transformers were replaced in the following way:

- The transformers used in the feeder under study had the following apparent power 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%, according to a Regional Power Utility.
- Lastly, the costs involved in replacing all the transformers were added up so that the total cost of the transformer replacement was known.

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

2.4 Replacing the dilapidated lines [18]

The dilapidated lines were replaced on the basis of the following:

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

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

2.5 Correcting the weak connections [18]

The weak connections in the network were corrected in the following way:

- The length of the lines connecting the buses was calculated 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 than 480 m.
- A gene was considered for each connection.
- The assumed number of the connections is true for the single-wire lines only. For the three-wire lines, the number should be multiplied by three.
- If a weak connection is corrected, the line resistance decreases by 0.001 ohms, according to the Qazvin Power Distribution Utility.
- Lastly, to calculate the total cost of correcting the weak connections, the operational costs related to correcting each connection was multiplied by the total number of connections (Eq. (7)).

$$C_{connection} = n_{connection} \times p_{connection} \quad (7)$$

Where:

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

2.6 The benefit obtained from the loss reduction [18]

The benefit obtained from reducing the power loss is calculated with Eq. (8).

$$B_{loss\_reduction} = (P_{loss-after} - P_{loss-before}) \times T \times LSF \times p_{energe} \quad (8)$$

Where:

- $B_{loss-reduction}$ - the benefit resulting from the loss reduction ($)
- $P_{loss-after}$ - the loss after applying the methods (kW)
- $P_{loss-before}$ - the loss before applying the methods (kW)

- T - the period, in hours, for which the energy loss was calculated. This covered the full duration of a year (8760 hours).
- LSF - loss factor
- p_{energe} - price of energy (\$/unit)

2.7 Objective function [18]

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

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

Where:

- OF - objective function
- $C_{imbalance}$ - the cost of adjusting the imbalance (\$)
- C_{cap} - the cost of the capacitor placement (\$)
- C_{trans} -the cost of the transformer replacement (\$)
- C_{line} - the cost of the conductor replacement (\$)
- $C_{connection}$ - the cost of correcting the weak connections (\$)
- $B_{loss-reduction}$ - the benefit resulting from the loss reduction (\$)

The OF flowchartis displayed in Fig. 3.

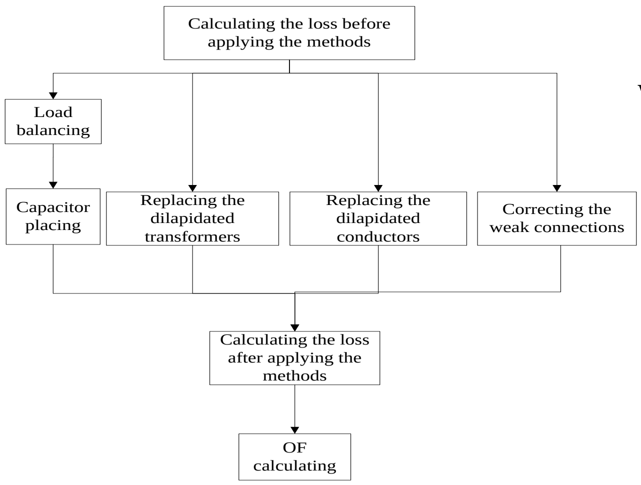

Figure 3: OF flowchart for each iteration

3 THE NEW METHOD

3.1 Load estimation

The load was estimated on the basis of the following:

- The data obtained from three power-quality analyzers installed and the feeder input
- The data about the foreseen power demand and the actual power consumption in the agricultural sector
- The total capacity of all the substations in the feeder
- The substations in the feeder were used by the agricultural and domestic sectors.
- The substations in the agricultural sector are either off or working at either peak load.

3.1.1 Load estimation for the agricultural substations:

The electric motor of an agricultural well is fed by a single transformer. The electric current which is fed into the electric motor is invariably at peak load unless the motor is off. That is to say, the current is always constant ($I_{A_i,h} = I_{A_i}$). The load of the agricultural substations is estimated from Eq.(10) below.

$$I_{A_i,h} = \frac{D_{c_i}}{\sqrt{3} \times V \times Cos\theta} \tag{10}$$

Where:

- $I_{A_i,h}$ - current of the i[th] agricultural substation at the h[th] hour of the year (A)
- I_{A_i} - maximum current of the i[th] agricultural substation (A)
- D_{c_i} - consumer demand for the i[th] agricultural substation (kW)
- V - secondary voltage (400 V)
- $Cos\theta$ - power factor

3.1.2 Load estimation for the domestic substations:

Since the current fed into the feeder under study was measured on the primary side (20 kV), the load of the domestic substations was estimated as follows: the total agricultural load was subtracted from the feeder input and the remainder was distributed among the substations according to their apparent power (Eq. (11)).

$$I_{S_i,h} = I_{f,h}\left(\frac{S_i}{S_T - S_{AT}}\right) \times \left(\frac{n_1}{n_2}\right) - \sum_{i=1}^{k} I_{A_i,h} \tag{11}$$

Where:

- $I_{S_i,h}$ -current of the i[th] domestic substation at the h[th] hour of the year (A)
- $I_{f,h}$ -current of the feeder input at the h[th] hour of the year (A)
- S_i -apparent power of the i[th] domestic transformer (kVA)
- S_T -total capacity of all the domestic and agricultural transformers (kVA)
- S_{AT} -total capacity of all the agricultural transformers (kVA)
- $\left(\frac{n_1}{n_2}\right)$ - the ratio between the primary voltage (20 kV) and the secondary voltage (400 V)
- k -the number of the agricultural substations (nine in total)

3.1.3 The approach to calculating the energy loss in the Sharif-Abad Feeder:

In order to calculate the energy loss in the feeder under study, the currents for the domestic and agricultural transformers were either measured or estimated for a year (equaling to 8760 hours). The data were then put into a software application which calculated the energy loss on the basis of these data using Eq. (12).

$$E_L = \int_T P_L(t)dt = \sum_T P_L(t).\Delta t \xrightarrow{\Delta t = 1hour} E_L = \sum_{h=1}^{h=8760} P_L(h) \tag{12}$$

Where:

- E_L -energy loss in a given period (kWh)
- P_L -power loss (kW)

- $P_L(h)$ -power loss at the h[th] (kW)

3.1.4 The approach to calculating the loss factor in the Sharif-Abad Feeder:

The loss factor is obtained using Eq. (13) below [19]:

$$LSF = \frac{E_L}{T \times P_L} \quad (13)$$

Where:

- LSF -loss factor
- P_L -power loss at the peak load (kW)
- T -period in hours (8760 h)

4 SIMULATION

4.1 Case study

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

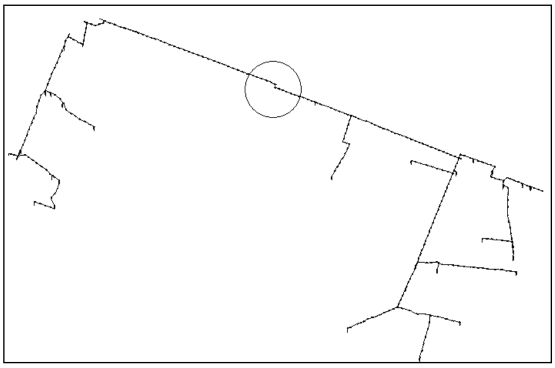

Figure 4: Schematic representation of the Sharif-Abad feeder.

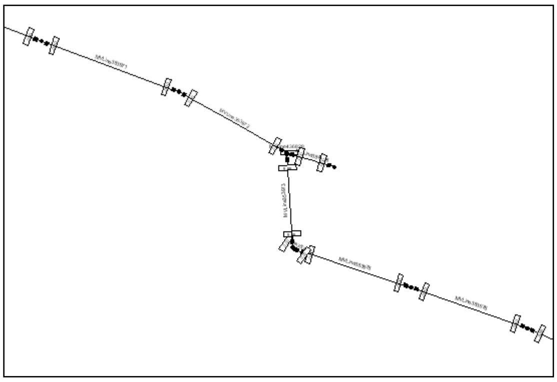

Figure 5: Enlargement of the area marked in Fig. 4.

Table 1 presents different levels of the apparent power as used in the network under study and the number of transformers associated with each level.

There are nine agricultural transformers in this feeder. Table 2 gives the number of the transformers associated with different levels of the apparent power used in the network.

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

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

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

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

The specification of this feeder is given in Table 3 and Table 4 below:

Table 3: 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(Ω/km)	X(Ω/km)	W(Ω/km)
1	0.2712	0.2464	450
2	0.4545	0.2664	255

Table 5 summarizes the operating costs of the methods applied.

Table 5: Operating costs

Cost	Item
Capacitor 12.5 kvar [$/unit]	136.550
Fixed cost 1 [$/unit]	100
Fixed cost 2 [$/unit]	200
Fixed cost 3 [$/unit]	300
Trans 25 kVA [$/unit]	2266.938
Trans 50 kVA [$/unit]	2707.938
Trans 100 kVA [$/unit]	3688.177
Trans 200 kVA [$/unit]	5602.810

Trans 250 kVA [$/unit]	5792.808
Trans 315 kVA [$/unit]	6863.947
Trans 500 kVA [$/unit]	10352.565
Trans 630 kVA [$/unit]	11970.326
Conductor type1 [$/kg]	4.092
Conductor type2 [$/kg]	4.246
Energy [$/kWh]	0.180

4.2 Software

DIgSILENT Power Factory 13.2 was used to develop the proposed algorithm to calculate OF and to analyze the system. Being an advanced software application for a simultaneous analysis of the power networks and control systems, DIgSILENT can calculate the 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 it very simple to apply the proposed method. OF was optimized using GA on the MATLAB R2008a software. A text file was used to connect the two applications.

4.3 Load estimation

4.3.1 Load estimation for the feeder input:

The data for the feeder input for all the days in August and September 2013 were obtained from the dispatching center, and the data for the current of the feeder input were available (the measurements were performed every hour). However, for the ten preceding months, i.e. October 2012-July 2013, we had to be selective, mainly for practical reasons. For this purpose, an appropriate day was chosen from each month. This means that the national holidays were excluded and that even the day of the week was taken into account. The hourly measurements taken each day were averaged. Each value was divided by the average current value of the best matching day in September 2013 to obtain the load coefficient for the associated month (i.e., the ratio between the average hourly measurement value for each chosen day and that for the best matching day in September 2013). Next, the hourly measurements for September 2013 (24*30=720) were multiplied by each of the ten load coefficients (Table 7). In this way we had the complete data for the ten preceding months. From these values that represent the current values of the feeder input for the whole year, the associated load curve was drawn (Fig. 6).

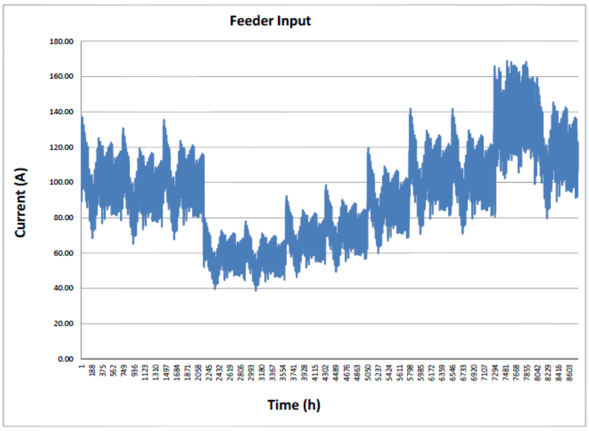

Figure 6. Load curve for the Shrif-Abad feeder input for the 12-month period under study.

4.3.2 Load estimation for the agricultural substations:

Table 6 presents the data for the consumer demand for each agricultural substation.

Table 6: Consumer demand for the Sharif-Abad agricultural substations

Substation	**Apparent power (kVA)**	**Consumer demand (kW)**
Well No. 1	100	66
Well No. 2	100	63
Well No. 3	100	75
Well No. 4	100	49
Well No. 5	200	82
Well No. 6	200	83
Well No. 7	100	71
Well No. 8	100	53
Well No. 9	200	83

Table 7: Load coefficients related to the months for which we had partial data

Month	**Chosen day**	**Day of the week**	**Average hourly measurement (kWh)**	**Best matching day in September 2013**	**Average hourly measurement (kWh)**	**Load coefficient**
Oct 2012	1st	Mon.	105.49	2nd	122.90	0.86
Nov 2012	5th	Mon.	101.01	2nd	122.90	0.82
Dec 2012	5th	Wed.	88.06	4th	104.01	0.85
Jan 2013	5th	Sat.	68.12	7th	136.71	0.50
Feb 2013	4th	Mon.	59.79	2nd	122.90	0.49
Mar 2013	4th	Mon.	71.62	2nd	122.90	0.58
Apr 2013	8th	Mon.	75.87	2nd	122.90	0.62
May 2013	6th	Mon.	92.07	2nd	122.90	0.75
Jun 2013	11th	Tue.	102.44	3rd	115.03	0.89
Jul 2013	6th	Sat.	121.42	7th	136.71	0.89

Table 8: The consumer demand of the Sharif-Abad agricultural substations

Month	Well No. 1	Well No. 2	Well No. 3	Well No. 4	Well No. 5	Well No. 6	Well No. 7	Well No. 8	Well No. 9
Oct 2012	0.42	0.64	0.43	0.78	0.66	0.55	0.65	0.65	0.28
Nov 2012	0.44	0.45	0.41	0.54	0.69	0.63	0.74	0.71	0.48
Dec 2012	0.30	0.31	0.26	0.76	0.44	0.23	0.42	0.04	0.15
Jan 2013	0.09	0.08	0.08	0.54	0.06	0.06	0.04	0.02	0
Feb 2013	0.01	0	0	0.23	0	0	0.06	0.04	0
Mar 2013	0.26	0.33	0.29	0.69	0.43	0.29	0.50	0.42	0.16
Apr 2013	1	0.65	1	0.70	0.74	0.56	0.78	0.78	0.33
May 2013	1	0.84	1	0.77	0.85	0.87	0.75	0.76	0.43
Jun 2013	0.69	1	0.05	1	1	0.58	1	1	1
Jul 2013	0.60	0.87	0.56	0.90	0.94	1	0.89	0.88	0.90
Aug 2013	0.84	0.83	0.37	0.82	0.87	0.91	0.79	0.79	0.78
Sep 2013	0.84	0.87	0.55	0.74	0.89	0.92	0.94	0.94	0.86

Table 9: The total number of hours each well was active in each month

Month	Well No. 1	Well No. 2	Well No. 3	Well No. 4	Well No. 5	Well No. 6	Well No. 7	Well No. 8	Well No. 9
Oct 2012	13	20	13	24	20	17	20	20	9
Nov 2012	13	14	12	16	21	19	22	21	14
Dec 2012	9	10	8	24	14	7	13	1	5
Jan 2013	3	2	2	17	2	2	1	1	0
Feb 2013	0	0	0	6	0	0	2	1	0
Mar 2013	8	10	9	21	13	9	16	13	5
Apr 2013	30	20	30	21	22	17	23	23	9
May 2013	31	26	31	24	26	27	23	24	13
Jun 2013	21	30	2	30	30	17	30	30	30
Jul 2013	19	27	17	28	29	31	28	27	28
Aug 2013	26	26	11	25	27	28	24	24	24
Sep 2013	25	26	17	22	27	28	28	28	26

The amount of the energy consumed by each well in each month in the period under study was obtained from the billing center of the distribution utility. Then, the month with the maximum energy consumed was assigned the value of 1. The value for each other month was calculated from dividing its energy consumption by the maximum amount of the energy consumed (Table 8). Next, the value for each month was multiplied by the total number of hours in that month. The product was the total number of hours each well was active in that month (Table 9).

4.3.3 Load estimation for the domestic substations:

The load of each domestic substation was estimated from Eq. (11) above.

4.4 Optimization technique

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

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

Next, the 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. They are used at a later stage by the genetic operators of the crossover and mutation to produce two offsprings for the new population. In the crossover, the genetic information between pairs, or larger groups, of individuals is exchanged. This research used a two-point crossover for recombination. If only the crossover operator is used to produce the 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 the future offsprings will have the same value at this position. This problem was solved with mutation, a process with which some of the genes were changed randomly. To ensure optimization globality both operators used the present work.[20].

4.5 Proposed algorithm:

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

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

The above-mentioned is only done if the imposed 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 $\begin{bmatrix} 1 \\ n_{\text{vars}} \\ n_{\text{vars}-imbalance} \\ n_{\text{vars}-cap} \\ population\_size \\ Generation \end{bmatrix}$ 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_{vars}, $n_{\text{vars}-imbalance}$, and $n_{\text{vars}-cap}$ identify the total number of the genes within the chromosome, those related to the load imbalance, and those associated 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, $B_1,\ldots,B_n$ are the new percentages of the imbalance for each load, $C_1,\ldots,C_n$ are the number of the 12.5-kvar capacitors for each load, $T_1,\ldots,T_n$ are the values of 0 or 1 related to each transformer, $L_1,\ldots,L_m$ are the values of 0 or 1 associated with each line, $X_1 \ldots X_k$ 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 operation and calculates OF using the chromosome given in that file. The application, then, inserts in the text file Flag 3 and the value of 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 GA.

5- If the maximum number of iterations is not reached, the process described above reverts to Stage 3. Otherwise, the process goes on to Stage 6 below.

6-GA is finished, so it inserts Flag 4 in 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

This study determined the energy loss, power loss at the peak load, and loss factor for the Sharif-Abad feeder and did the following with regard to the attendant costs:

- Adjusting the load imbalance
- Placing the capacitors
- Replacing the transformers
- Replacing the line conductors
- Correcting the weak connections

5.1 Energy loss

The energy loss in this network was found to be 505.295544 MWh.

5.2 Power loss at the peak load

The active-power loss was found to be 0.142529 MW at the peak load.

5.3 Loss factor

Dividing the amount of the energy loss by that of the active power loss using Eq. (13) gives us the loss factor for the year under study: 0.4047.

5.4 Adjusting the load imbalance

Table 10 summarizes the results of adjusting the load imbalance in transformers.

The power loss was 129.389 kW after the load imbalance was corrected, indicating a drop of 13.14 kW, which equals to 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 the average current. The quantities of phase currents S and T were 0.8 and 0.7 times the average current, respectively. Phase current R was by 50% more than the average current. Phase currents S and T were by 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 the cost of $112.7. The loss reduction thus obtained will be 21 MWh, and the resulting benefit will be $3700 a year.

Table 10: Fixing the load imbalance

Item	Quantity
Loss after run [kW]	129.389
Loss reduction [kW]	13.140 kW
Cost [$]	1234.419
Benefit [$]	8453.307
|OF| [$]	7218.888

5.5 Capacitor placement

Unless the load imbalance had been adjusted, the capacitors could not be placed. Hence, the loss should have a different value before capacitor placement than before deployment of any of the other methods. The results of the capacitor placement in the network are given in Table 11.

Table 11: Capacitor allocation

Item	Quantity
Loss before run [kW]	135.719
Loss after run [kW]	112.783
Loss reduction [kW]	22.936
Cost [$]	12677.8
Benefit [$]	14755.802
|OF| [$]	2078.002

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.

Before capacitor placement and at the peak load, the apparent-power input was 4368.262 kVA, the reactive-power input was 2143.851 kvar, and the power loss was 135.719 kW. After placing the capacitors and at the peak load, the apparent-power input was 3973.889 kVA, the reactive-power input was 1216.810 kvar, and the 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 the power loss by 22.936 kW (i.e., 16.90%).

The total capacity of all the capacitors added to the network was 950 kvar at the peak load of the year. The capacitor placement increased the usable capacity of the network by 394.373 kVA (equal to 9.03%) at the peak load of the year.

5.6 *Replacing the transformers*

The zero transformers had to be changed. This finding can be explained as follows:

There were 28 transformers in the feeder studied in this research. The total loss of the transformers consists of copper and iron loss. At the peak load of the year, the total loss of all the transformers was 31 kW, with the total iron loss of 19 kW, and the total copper loss of 12 kW. The total loss of all the transformers was 54.82% of the total loss of the network. The iron loss was 60.29% of the total loss of the transformers and 33.05% of the total loss of the network. The copper loss was 39.71% of the total loss of the transformers and 21.77% of the total loss of the network.

Replacing the dilapidated transformers will reduce the total loss of the transformers by 20%. That is to say, a reduction of 55.4 MWh will bring the total loss of the transformers to 221.6 MWh. It follows that the total loss of the network will reduce by 10.96%. Given that the benefit of the loss reduction resulting from replacing the dilapidated transformers will be $7523 a year, and that replacing all the transformers will cost $152633, the benefit to be obtained from replacing the dilapidated transformers will not be significant

5.7 *Replacing the line conductors*

The total line loss was 228.30 MWh, equaling to 45.18% of the total loss of the network. Replacing the dilapidated conductors of a line diminishes its resistance by 10%. This correspondingly reduces the loss of the lines as the loss is positively related to the resistance. Thus, replacing all the dilapidated conductors will result in a reduction of about 4.52% in the total loss of the network. The loss will be reduced by 22.83 MWh. The benefit to be obtained will be $4109.4 a year. Replacing all the conductors will be approximately $114000 given that all the lines in the network are about 19 km long. As a consequence, the benefit to be obtained from replacing the dilapidated conductors will be insignificant. Table 12 summarizes the results of the line conductor replacement.

Table 12: Replacing the line conductors

Item	Quantity
Loss after run [kW]	142.234
Loss reduction [kW]	0.295
Cost [$]	166.089
Benefit [$]	189.787
|OF| [$]	23.698

5.8 *Correcting the weak connections*

The weak connections should not be corrected. The explanation is as 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 the weak connections is 0.08% of the total resistance of the line. Fixing the weak connections in a line will cost $1.406.

The loss is positively related to the resistance. The loss emanating from the weak connections constitutes 0.08% of the loss caused by the resistance. The loss resulting from the network lines is 45.18% of the total loss of the network. Therefore, the loss induced by the weak connections is 0.036% of the total loss of the network. That is, the total loss resulting from the 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 the weak connections in the network under study was 2514, $3534 will be needed to fix all those connections. The benefit to be obtained from fixing the weak connections seems trivial compared to the costs involved.

5.9 *All the methods applied simultaneously*

Different capacitors were installed 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 buss 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.

Table 13 presents the results of a simultaneous application of all the methods.

Table 13: All the methods applied simultaneously

Item	Quantity
Loss after run [kW]	116.734
Loss reduction [kW]	25.795
Cost [$]	14008.043
Benefit [$]	16460.424
|OF| [$]	2452.381
Cost of Fixing load imbalance [$]	437.843
Cost of Placing capacitors [$]	13570.200

Of all the five loss–reduction methods, only placing the capacitors and fixing the load imbalance seem cost-effective. More specifically, simultaneously applying all the methods reduces the power loss by 18.10%, with the benefit-cost ratio being 47 to 40. The total capacity of the capacitors added to the network was 1050 kvar.

Table 14 and Table 15 summarize the benefit-cost ratio and the percentage of the loss reduction, respectively. The best method of the loss reduction will be fixing the load imbalance providing that the decision is based on the benefit-cost ratio. However, if the percentage of the loss reduction forms the basis of the decision, the capacitor placement will be the best method.

Table 14: benefit-cost ratio

Method	benefit-cost ratio
Fixing load imbalance	6.85
Placing capacitors	1.16
Replacing line conductors	1.14

Table 15: Percentage of the loss reduction

Method	percentage of loss reduction
Fixing load imbalance	9.22
placing capacitors	16.09
Replacing line conductors	0.21

CONCLUSION

This study proposes a way for evaluating five different methods of reducing the power loss in an actual distribution network in terms of the degree of the loss reduction brought about and the amount of the costs involved. In addition, a model is proposed for load estimation. Another important aim of this study was to calculate the energy loss, power loss at the peak load, and loss factor for the observed network. The results show that fixing the load imbalance and placing the capacitors are the best loss–reduction methods. The former is advisable if our decision is to be based on the benefit-cost ratio. However, if it is the percentage of the loss reduction that should be considered, the latter method is the better choice. It is shown that the general pattern of the load curve of each substation estimated by the proposed method is quite similar to the pattern obtained from the actual measurements. It should be noted at this point that the present study is limited in that the load estimation is based on the measurements only performed over two months. Thus, it would be advisable to replicate this work with year-long measurements. Finally, when the model is put into operation, the load imbalance adjustment should always be performed prior to capacitor placement. No particular order is needed for performance other loss-reduction methods.

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