Journal of Intelligent Procedures in Electrical Technology, Vol.9, No.36, Winter 2019

Investigation of Capacitor Placement in Variable Loads to Reduce the Power Loss of Distribution Systems Using Mixed–Integer Linear Programming Algorithm and Re–Gradation of Loads

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Received: 2018/3/30 Accept: 2018/12/16

Abstract: Capacitor placement at substations is one of the effective methods for loss reduction and efficiency increasing of power systems. In this paper, a novel method for capacitor placement on the secondary side of the distribution transformers is carried out. The mathematical method of Mixed–Integer Linear Programming (MILP) algorithm is used for paper goal to increase the Net Present Value (NPV), resulting from the loss reduction. Due to the variability of the loads, a special template is used for loads modelling. Not only the constant loads, but also three types of industrial, residential and commercial loads are assessed with the proposed method. Then, the results are discussed in order to re–grade loads. Also, the proposed method is compared with two methods of Particle Swarm Optimization (PSO) algorithm and Teaching–Learning Based Optimization (TLBO) algorithm. All of the tests are simulated with MATLAB software and total time of problem is considered as ten years.
Index Terms: Distribution systems, Capacitor placement, Variable loads, Mixed–Integer Linear Programming (MILP) algorithm, Loss Reduction, Net Present Value (NPV).

بررسی جایابی خازن در بارهای مختلف برای کاهش توان تلفاتی سیستم توزیع با استفاده از الگوریتم برنامه‌ریزی خطی و درجه‌بندی دوباره بارها

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خلاصه: شبکه‌های توزیع برق امروزه دارای بارهای مختلف و متغیری هستند که هرکدام الگوهای مصرف مخصوص به خود را دارند. این بارها هرکدام دارای توان تلفاتی مشخصی هستند. یکی از راه‌های مؤثر برای کاهش توان تلفات و افزایش بازده در شبکه‌های توزیع برق، استفاده از جایابی خازن در پست‌های برق است. در این مقاله جایابی خازن در طرف ثانویه ترانسفورماتورهای شبکه توزیع انجام می‌شود. روش ریاضی برنامه‌ریزی اعداد صحیح برای جایابی خازن به منظور افزایش سود خالص حاصل از کاهش تلفات استفاده می‌شود. با توجه به تغییر اندازه بارها، یک الگوی ویژه برای مدل سازی انواع مختلف بارهای متغیر استفاده می‌شود. علاوه بر بررسی مشکل بارهای ثابت، روش پیشنهادی برای سه نوع بار صنعتی، مسکونی و تجاری مورد آزمایش قرار گرفته است و نتایج به دست آمده از همه زمان‌ها بر کاهش ضرر و افزایش سود مالی پروژه برای درجه‌بندی دوباره همه بارها مورد بحث قرار گرفته است.

کلمات کلیدی: شبکه‌های توزیع، جایابی خازن، بارهای متغیر، برنامه‌ریزی اعداد صحیح آمیخته، کاهش تلفات.

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1. Introduction

Recently, power systems losses have been increased gradually. In these systems, the number of end–user loads are increasing which most of them have nonlinear traits. The more power consuming, the more power loss, and then, it causes more financial losses. For this, the optimization of the power system is necessary. The most commonly methods, to enhance the efficiency of distribution networks, include system reconfiguration [1], installation of distributed generation (DG) units [2], shunt capacitor placement [3], improving voltage profile, and providing optimal design of the power system.

Till now, several techniques and algorithms are used for optimization as scientific researches and practical projects. Generally, the method used in scientific studies can be categorized into two general methods based on the probability (guesswork) method and the mathematical method (mathematical logic). In the first method, which is also known as the evolutionary algorithm (EA), the sketch of the algorithm is inspired via nature and its components. In the second method, the algorithm is based on the error limitation between initial the main responses of the problem and this error is reduced by mathematical equations.

The goal of this paper is that how the capacitor placement can reduce the power loss and how much is the capacitor costs. The main purpose of capacitor placement in the power system is to compensate the reactive power of the system; as a result, it will increase the voltage level and thus reduce the power losses. By that, the power factor of the system is increased considerably [4]. Also, both of the series and shunt connection of capacitor are used in the transmission network; but only the shunt connection of capacitor is used in the distribution networks. Furthermore, most of the end–user loads are inductive and need enough reactive power to be provided. To avoid this instability of power systems, several preventive steps have been proposed, one of them is the shunt capacitor installation [5].

Other goals in load compensation include improved voltage regulation and load balancing [4]. To solve these problems with saving in energy, reducing cost, increasing in reliability and power quality, the shunt capacitors are installed on the radial feeders for reactive power injection [6]. In order to reach these aims, various methods have been proposed. Most of the presented formulations consider the minimization of the energy losses and the peak power losses of the circuit as well as the cost of the capacitors [7].

In [8], a new method for placement of the capacitors in all available positions of nodes and controllable switches; the object function of this method are the reduction of total cost. The drawback of this algorithm is its large search time, while having worth cost reductions. A new method called hybrid CODEQ (HCODEQ) to overcome the drawback of parameters selection in the differential evolution is proposed in [9]. Jannat and Savic [10] proposed a novel method based on application of the Monte Carlo simulation methods, for optimal capacitors allocation with considering to DG, and load demand. Decision making approach is used for shunt capacitor placement in [11].

An optimization technique based on plant growth to locate the capacitor in power systems has been used in [12]. Reference [13] presents a new capacitor placement method based on particle swarm optimization (PSO) algorithm. A new method called Whale Optimization Algorithm (WOA) for a typical radial distribution system is used to find optimal sizes and places of shunt capacitors by [14]. A new PSO algorithm for problems of capacitor placement and network reconfiguration in the presence of non-linear loads is proposed in [15]. Araujo et al tested new capacitor placement in several unbalanced distribution systems for loss reduction and voltage profile increasing in [16]. The multi–objective optimization algorithm NSGA-II is developed in [7] for capacitor placement and effectiveness of the proposed procedure is assessed by a practical example. New method based on flower pollination algorithm is proposed in [14] for optimal location and sizing of shunt capacitors.

Other methods for capacitor placement, based on heuristic methods, includes: Harmony Search Algorithm (HSA) [17], Improved HSA (IHSA) [18], Genetic Algorithms (GA) [19], Flower Pollination Algorithm (FPA) [20], fuzzy expert system [21], Fuzzy–Hybrid PSO (HPSO) [22], Fuzzy–GA [23], etc.

Usually, the distribution network end–user loads produce harmonics because of using power electronic devices and presence of controllers in them, which causes an imbalance current and voltage. As a result, a nonlinear load characteristic, especially for industrial loads, is created. These features can be modeled approximately based on mathematical equation. There are several models for description of different loads in distribution systems. Authors in [24] proposed a new Penalty Free Genetic Algorithm (PFGA) for optimal capacitor placement which performed different load models. For that, the admittance of loads depend on demand active and reactive powers. In [25], the defined models of load, consist of active and reactive powers, are depended on voltage and operation active and reactive powers, respectively. Consequently, the optimal capacitor sizing and placement problem is changed to a nonlinear type.

In this paper, the Mixed Integer Programming (MIP) is used to solve profitability of capacitor placement problem in distribution network to minimize power losses and improving voltage profile. With the aim of solving the problem, the Net Present Value (NPV) of the capacitor placement in network is considered as the objective function that is defined based on the network losses. In order to find the number and size of the capacitors in the network, obtained equations are solved through the MIP algorithm. Simulations have been done in MATLAB software and the results are fully analyzed for various fixed and variable loads to verify the advantage of the proposed method. The contribution of this paper is to examine the costs and benefits component and the financial benefit of the capacitor placement for a variety of four loads, including industrial, residential, commercial and constant. In previous articles, these costs were only explored for constant loads. Also, we compared the proposed method with two other methods of PSO and TLBO algorithms.

The remaining sections of paper are organized as follows: In section 2, the mathematic formulas of distribution systems power losses and variable types of consumed loads are presented. In section 3, NPV for capacitor placement and its all costs are studied. In section 4, the MIP algorithm is introduced. Section 5 presents the results of computer simulations. Finally, conclusions are drawn in Section 6.

2. Analysis of Distribution Network Losses and Loads

2.1. Mathematical modeling of losses

The distribution network consists of two types of losses: transformer losses and feeder losses. A transformer can be modeled based on its resistance and reactance. Fig. 1 shows the equivalent circuit of a distribution transformer. In this figure, **I** represents the flowing current through the transformer, **R** and **X** are the equivalent impedance and reactance, respectively. Finally, **V1** and **V2** are also the effective values of the primary and secondary voltages of transformer, respectively.

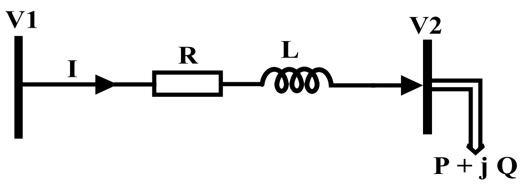

Fig. (1): Equivalent circuit of distribution transformers

As the losses of a transformer depend on its impedance and current flow, it can be modeled by the following equations:

$$\begin{cases} \vec{I} = I_R + jI_X \;\Rightarrow\; \left|\vec{I}\right| = \mathrm{I} = \sqrt{\left(I_R\right)^2 + \left(I_X\right)^2} \\ S_{LOSS} = P_{LOSS} + j\,Q_{LOSS} = \mathrm{I}^2.Z = \mathrm{I}^2.\left[R + jX\right] \end{cases} \quad (1)$$

$$\Rightarrow\; S_{LOSS} = \left[\left(I_R\right)^2 + \left(I_X\right)^2\right].\left[R + jX\right] \quad (2)$$

where, I_R and I_X are the active and reactive components of I, respectively; S_{LOSS}, P_{LOSS}, and Q_{LOSS} are the total complex, active and reactive power losses, respectively; and Z is the complex impedance. From Eq. (2), P_{LOSS} can be calculated as follows:

$$P_{LOSS} = \left[\left(I_R\right)^2 + \left(I_X\right)^2\right].R = R\left(I_R\right)^2 + R\left(I_X\right)^2 \quad (3)$$

The active (**P**) and reactive (**Q**) consuming powers of the transformer in secondary are available (see Fig. 1). Therefore, Eq. (3) for the i'th transformer be rewritten:

$$\begin{aligned} P_{LOSS}^{TR}(i) &= R_i \cdot \left(\frac{P_{Li}}{V_{i2}}\right)^2 + R_i \cdot \left(\frac{Q_{Li}}{V_{i2}}\right)^2 \\ &= P_{LOSS,R}^{TR}(i) + P_{LOSS,X}^{TR}(i) \end{aligned} \quad (4)$$

where, $P_{LOSS}^{TR}(i)$ is the total active power losses of the i'th transformer, P_{Li} and Q_{Li} are the active and reactive power consumptions of the load connected to the secondary side of the i'th transformer, V_{i2} is the secondary voltage, $P_{LOSS,R}^{TR}(i)$ and $P_{LOSS,X}^{TR}(i)$ is the active power losses of the transformer due to the Real and Imag. components of I, respectively.

If a load hasn't reactive power, **Q=0**, its active power losses will be equal to zero, $P_{LOSS,X}^{TR}(i) = 0$. So, the total losses of the transformer are equal to the active losses due to the active power, i.e. $P_{LOSS}^{TR}(i) = P_{LOSS,R}^{TR}(i)$. Therefore, minimizing the reactive power consumption is selected as the main goal of paper.

Another type of active power losses are related to distribution network feeders parameters. Like transformer losses, the active power losses due to reactive power of load in the feeder between buses i and $i+1$ can be obtained as follows:

$$P_{LOSS,X}^{Line}(i, i+1) = R_{i,i+1} \cdot \left(\frac{Q_i}{V_{i1}}\right)^2 \quad (5)$$

where, Q_i is the reactive power consuming in bus i, $R_{i,i+1}$ is the feeder resistance between buses i and $i+1$, V_{i1} is the primary voltage of the transformer in bus i. Using Eq. (4) and Eq. (5), the total active power losses of a radial network with N buses and N–1 feeders, due to reactive loads, are defined by Eq. (6):

$$P_{LOSS,X} = \sum_{i=1}^{N-1} P_{LOSS,X}^{Line}(i, i+1) + \sum_{i=1}^{N} P_{LOSS,X}^{TR}(i) \quad (6)$$

2.2. Modeling of various end–user loads

End–user loads in the distribution network, depending on the their application, have different variations.

Generally, according to the intensity and value of the power consumption, the loads can be divided into four categories as "constant", "residential", "commercial", and "industrial" [25]. In order to model the variable loads performance, the following mathematical relation can be presented [25]:

$$P_i = P_{0i} \times (V_i)^{\alpha} \quad , \quad Q_i = Q_{0i} \times (V_i)^{\beta} \tag{7}$$

where P_i and Q_i are the total active and reactive power consumption of bus i, respectively; P_{i0} and Q_{i0} are active and reactive power operation point at bus i respectively; V_i is the primary voltage of bus i, and α and β are called active and reactive power exponents, respectively. The values of α and β for various loads are given in Table (1) [25].

Table (1): Various end–user loads exponents

Load Type	α	β
Constant	0.00	0.00
Residential	0.92	4.04
Commercial	1.51	3.40
Industrial	0.18	6.00

3. Net Present Value of the Capacitor Placement

To be successful in the installation of a capacitor in a distribution network, the NPV obtained from it must be positive. In this paper, the NPV function has been considered as the objective function. Then, the value of the objective function should be maximized using the optimization algorithm. The annual cost function owing to the power losses, C_t, in **$**, can be defined as follows [3]:

$$C_t = \hat{P}_{LOSS,X} \times F_{LOSS} \times K_{E.t} \times 8760 \tag{8}$$

where, $\hat{P}_{LOSS,X}$ is the maximum power losses (losses obtained at peak load) in kW, F_{LOSS} is the power loss factor, which can be defined as ratio of average power loss to maximum power loss; and $K_{E.t}$ is the energy price in per year in **$**/kWh, which has the direct relation with the inflation rate and can propose as follows:

$$K_{E.t} = K_{E1} \times (1+r)^{(t-1)} \tag{9}$$

where, K_{E1} is the energy price in the first year, r is the annual inflation rate in percent (%), and t is the year that the energy price is calculated.

In order to calculate the NPV, the investment costs should be considered. These costs include the purchase, installation, and maintenance of capacitor units, which are considered for first year. Therefore, the NPV function can be formulated as follows:

$$NPV = \sum_{t=1}^{T} \frac{B_t}{(1+d)^t} - IO \tag{10}$$

where, NPV is in **$**, B_t is the profit of year t in **$**, d is the reduction factor of energy price, IO is the total cost spent on initial investment includes the purchase and installation of the capacitor in $, and T is the total duration time of the project. Furthermore, B_t is defined as:

$$B_t = b_t - OM_t = \left(C_t^{New} - C_t^{Old}\right) - OM_t \tag{11}$$

where, b_t is the annual saving in **$**, C_t^{Old} and C_t^{New} are the annual costs of casualties for the before and after capacitor installation, respectively, which are obtained from (7), and OM_t is the annual operation and maintenance costs as defined below:

$$OM_t = \left[\sum_{i=1}^{N} x_i\right] \times K_O \tag{12}$$

where K_O is the annual operation and maintenance cost of the capacitor bank installed for each transformer, and x_i determines the presence/absence of capacitor bank in i'th transformer, and equals to zero or one (binary variable).

The following approximate formula can be used to calculate the cost of purchasing and installing a capacitor (IO), which is performed only in the first year.

$$IO = IC + PC \tag{13}$$

where,

$$IC = \left[\sum_{i=1}^{N} x_i\right] \times K_I \quad , \quad PC = \left[\sum_{i=1}^{N} x_i \times L_i\right] \times K_P$$

where, K_I and K_P are the purchase cost of the capacitors unit and installation cost for each transformer, respectively; and L_i is the number of capacitor units.

Considering that the purchasing cost is reduced gradually by increasing the capacitor bank size, the following formula can be used to fit PC size in Eq. (13):

$$PC = \sum_{i=1}^{N} x_i \times L_i \times (K_P - \mu \cdot L_i) \tag{14}$$

where, μ is the reduction price factor.

By inserting Eq. (8), Eq. (9) and Eq. (11) to Eq. (14) in Eq. (10), the final equation for calculating total net profits in terms of power losses, number of capacitors in each buses, and investment costs are obtained as follows and solved by the proposed algorithm using equation:

$$NPV = \sum_{t=1}^{T} \Bigg\{ \Bigg(\Big[\left(\hat{P}_{LOSS,X}^{New} - \hat{P}_{LOSS,X}^{Old}\right) \times F_{LOSS} \times K_{E1} \times (1+r)^{(t-1)} \times 8760 \Big] - \left[\left(\sum_{i=1}^{N} x_i\right) \times K_O \right] \Bigg) \Big/ (1+d)^t \Bigg\} - \left[\sum_{i=1}^{N} x_i\right] \times K_I \tag{15}$$

4. Mixed Integer Programming Algorithm

The superiority of mathematical–based algorithms to the probability–based algorithm is that the answer is the best solution possible for the problem being solved. Also, the accuracy and speed of computing have a high impact on the final answer.

One of the mathematical algorithms developed by George B. Dantzig in 1947 was integer programming (IP), which nowadays is used extensively and widely for complex problems. This algorithm uses different methods to solve the problem.

There are three types of variables in the all IP problems: Pure Integer, Mixed Integer, and Binary Integer. Also, there are two type of equation defined for IP algorithm that can be either linear or nonlinear quadratic. Various methods have been proposed to solve these algorithms, some of which are common to all algorithms, and others are unique to a particular type of algorithm.

As mentioned before, the optimal capacitor placement problem is a nonlinear problem. Furthermore, as for the Eq. (15) is a quadratic problem, the nonlinear Mixed Integer Quadratic Programming (MIQP) algorithm by branch and bound solving method and CPLEX economic package is used in MATLAB software. The Flow–Chart for solving the problem with the desired algorithm is shown in Fig. 2.

5. Computer Simulation Results

In order to illustrate the advantages of the proposed method in this paper, a real system is simulated. The main specification of the data is tabulated in Table (2). Fig. 3 shows a single–line diagram of the desired distribution network. The parameters for lines, transformers, and loads are tabulated in Appendix. 1 [3]. As explained in the section 2, four various loads can be considered that are used in this paper. Also, the active and reactive power values presented in [3] are considered as the constant load and other loads will be determined based on this loads. In the first step, we considered that all loads are constant. Then, after simulation for all three methods, the sizes and locations of the capacitor units are tabulated in Table (3). In some buses such as 16–18, 21, and 29, the reactive power consumption causes the number of capacitor units increase. For better describing, Fig. 4 shows a comparison between reactive power consumption of buses and the total capacity of capacitor units that are obtained by various methods. As this figure shows, none of methods couldn't cover 100% of bus consumption.

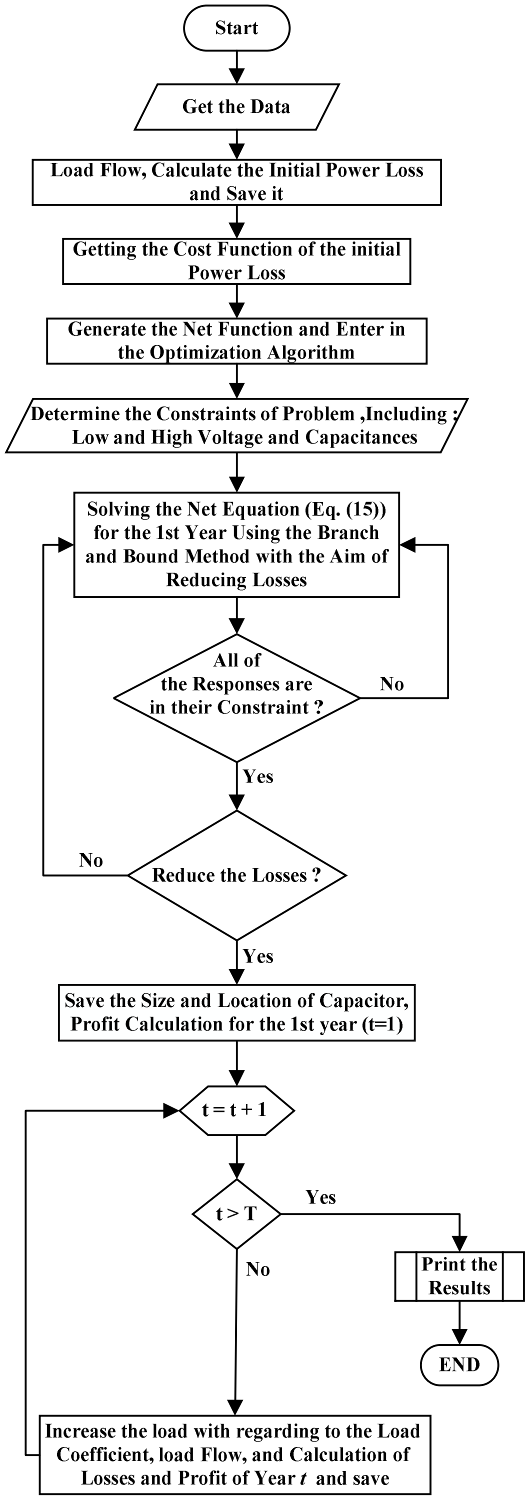

Fig. (2): Flowchart of the solving of the problem

Table (2): Main Features of Studied Network

Parameter Description	Symbol	Value
Primary Voltage of Transformer (kV)	V_{i1}	11
Secondary Voltage of Transformer (V)	V_{i2}	400
Reference voltage (voltage bus1) (p.u)	V_1	1.01
Total number of network bus	N	35
Capacity of the smallest capacitor bank (kVar)	Q_c^{min}	25
The price of the smallest capacitor bank ($)	K_P	5000
Reduction price factor	μ	20
Cost of Installing Capacitor Bank ($)	K_I	7000
Annual cost of holding the capacitor bank ($)	K_O	800
Energy price ($/kWh)	K_E	1.4
Inflation rate to increase energy prices (%)	r	10
Annual profit reduction rate	d	7
Annual Growth Rate (%)	l	6
Loss factor	F_{LOSS}	0.5
Total time for project (year)	T	10

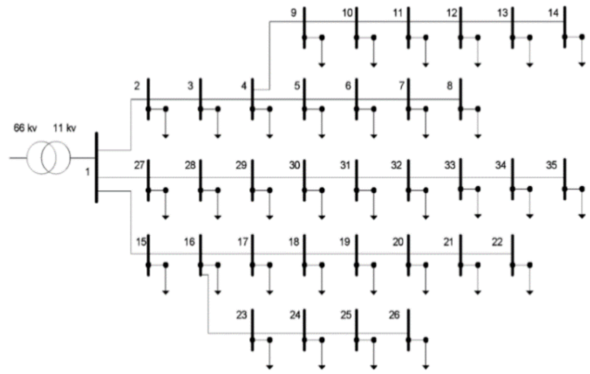

Fig. (3): Single–line diagram of the distributed network

5.1. Constant Load

The results of computer simulation for constant loads are summarized in Table (4). As seen in this table, the power losses in the first year were calculated to be 21.18 kW, which the total loss of transformers is 13.08 kW (about 62%) and the total power loss of the total network feeders is 8.10 kW (about 38%). After optimization by three methods, the power losses are calculated as 3.76 kW for MIQP, 4.01 kW for PSO, and 4.13 kW for TLBO. Then the maximum loss reduction obtained by MIQP, which is 82%. As seen in Table (4), the power loss of last year before capacitor installation 60.48 kW, and after installation, the best result 23.13 kW that are obtained by MIQP algorithm. In minimum voltage of buses, the TLBO algorithm has best performance and it raises the voltage profile from 0.9740 p.u. to 0.9743 p.u., while the other methods have lower increasing. Against that, the NPV of propose method is maximum and the total costs of this method are minimum, due to minimum capacitor units (see Table (3)).

All components of the active power losses, including lines and transformers losses are drawn in Fig. 5. The effective voltages of all buses before and after capacitor placement are shown in Fig. 6.

5.2. Industrial Load

In the variable loads, the size of active and reactive power consumption of loads varies with the voltage value. Therefore, a similar result can be expected for a constant load. After the simulation, the size and location of the capacitor banks, as predicted before, were obtained in accordance with Table (3). The results for industrial loads are summarized in Table (5).The power loss for industrial load, before installation of capacitor banks was 20.334 kW and after optimization, the power loss obtained as 4.00, 4.18, and 4.36 kW for MIQP, PSO, and TLBO, respectively. This means that decrease of power loss for MIQP method is 80%. Also, the NPV of the proposed method is more than other desired methods. The power loss of feeders, power loss of transformers, the voltage profile of buses, and NPV in 10 years for all three methods and before capacitor placement are shown in Fig. 7. The results are similar to constant loads results. In Fig. 7–d, the NPV for MIQP algorithm are more than others in all years. Voltage profiles in all buses is maximum for TLBO algorithm and minimum for PSO algorithm as shown in Fig. 7–c.

5.3. Residential load

The results for this type of loads are summarized in Table (6). As seen in this table, the active power losses for residential load, before capacitor banks installation was 20.547 kW. In other hand, the power loss after that for MIQP, PSO, and TLBO algorithms are 3.923, 4.12, and 4.28 kW, respectively. The NPV of MIQP is maximum.

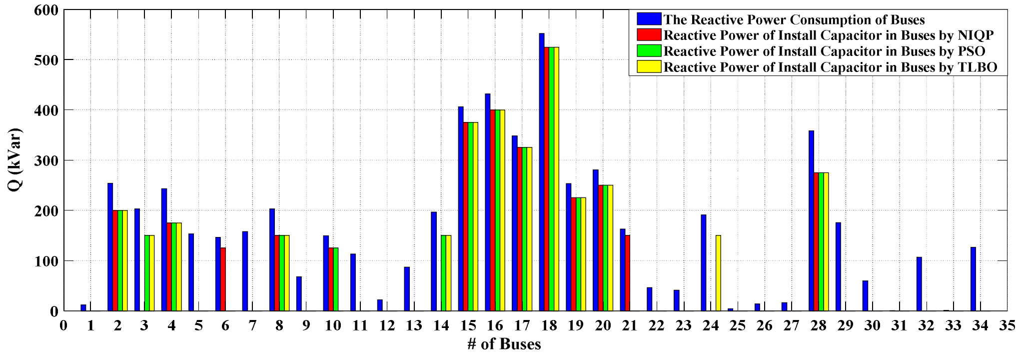

Fig. (4): Reactive power of buses consumption and total capacitor units obtained by MIQP, PSO, and TLBO

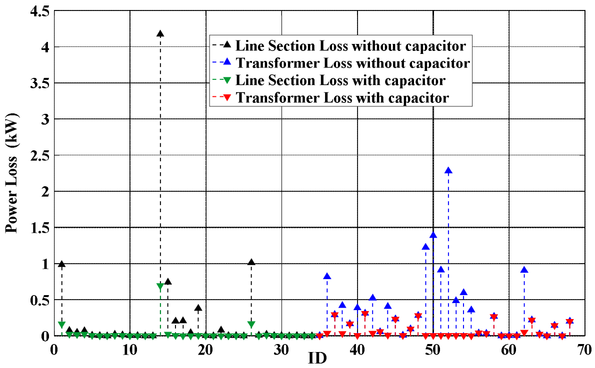

Fig. (5): The power losses components before and after capacitor installation for constant loads

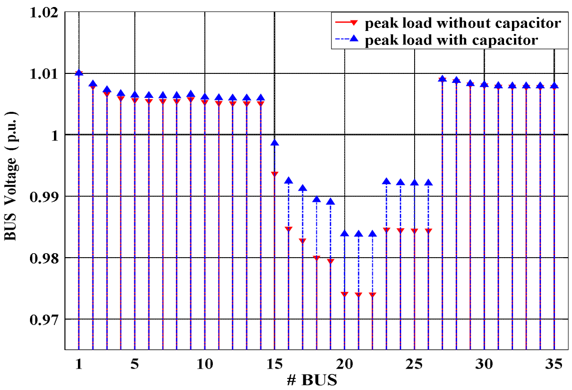

Fig. (6): The magnitude of effective voltages of the busses before and after capacitor installation for constant loads

5.4. Commercial Load

The results for this type of load are summarized in Table (7). For commercial load, the active power losses before the capacitor placement was 20.632 kW. After placement with different methods, the power losses are obtained 3.89, 4.10, and 4.26 kW for MIQP, PSO, and TLBO, respectively.

5.5. Comparison

As mentioned before, the investigated loads NPV for the proposed method are maximum based Tables (4)–(7). Furthermore, power loss in proposed method has been decreased more than PSO and TLBO. Also, the highest NPV in the all years is obtained for constant loads. This is represented in Fig. 8. This issue reflects this fact that in addition to the obvious advantages of constant load, such as the minimum voltage fluctuation, the NPV in the capacitor placement project is the highest value. In other variable loads, commercial and industrial loads have the highest and lowest NPV, respectively; which can be considered proportional to the reverse of loads exponents. This proportion is also visible in voltage variations; the maximum increase in voltage size for constant load is (0.0099 p.u) and minimum increase for industrial load is (0.0087 p.u). In the decreases of the $\hat{P}_{LOSS,X}$, the minimum and maximum value is related to the industrial load (with a decrease of 16.33 kW for the first year and 35.86 kW for the last year), and constant load (with a decrease of 17.42 kW for the first year and 37.35 kW for the last year). Note that these losses is directly related to the variation in reactive power consumption and the lowest losses were recorded in industrial load. Therefore, according to the conditions and factors mentioned, including profit value, the minimum voltage, the minimum voltage variation in each bus, the value or the decrease in power losses, various decisions can be made.

As a results, it can be seen that the constant load is better for consumers and utilities. But due to the existence of a variety of power–electronic equipment, the loads behavior changes periodically or even momentarily. So, voltage control will be harder. Today, more advanced equipment and devices are used to control the size of capacitive banks, which are more expensive than their old ones. If we want to analyse the voltage profiles, minimum and maximum voltages before capacitor placement were related to constant and commercial loads, respectively. After placement, TLBO algorithm has the best.

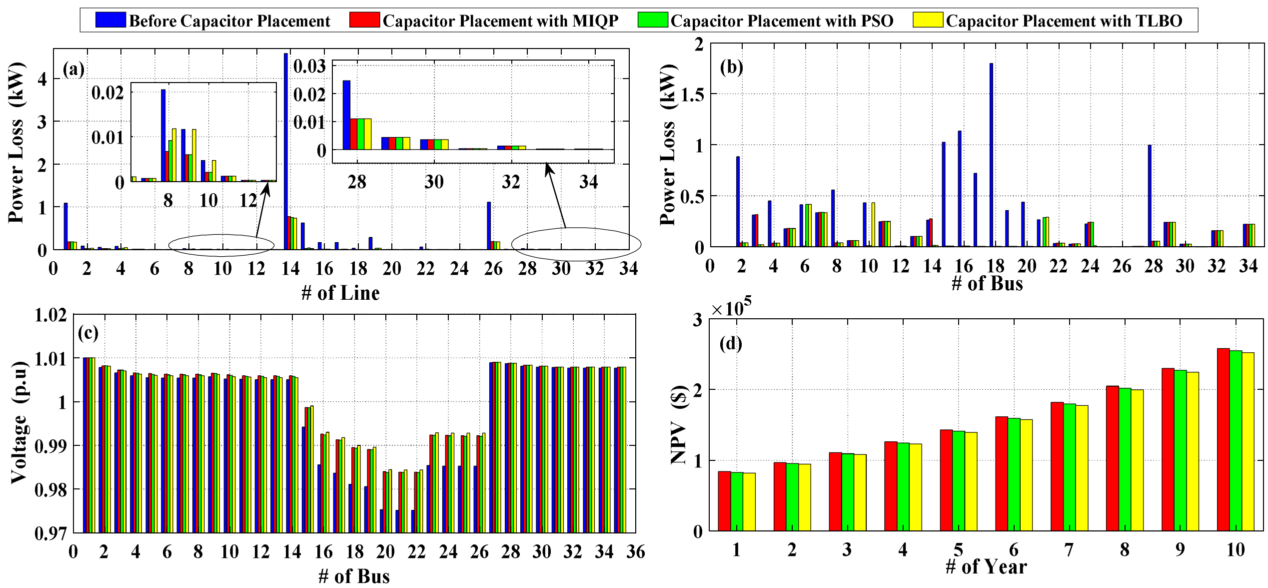

Fig. (7): Results for Industrial Loads: a) Power losses of feeders, b) Power loss of transformer, c) Bus voltages, d) NPV

response, while minimum voltage value is related to constant loads and maximum is obtained from commercial loads.

6. Conclusion

In this paper, MIQP algorithm has been used for the capacitor placement in constant load and variable loads. Also, in comparison with other methods as PSO and TLBO algorithms, the proposed method has better results in NPV values and power loss minimization. After assessing of the results, constant loads have maximum NPV and power loss reduction. In general, the main result was that with increasing sensitivity loads to voltage changes, NPV decreases, voltage changes and loss increases.

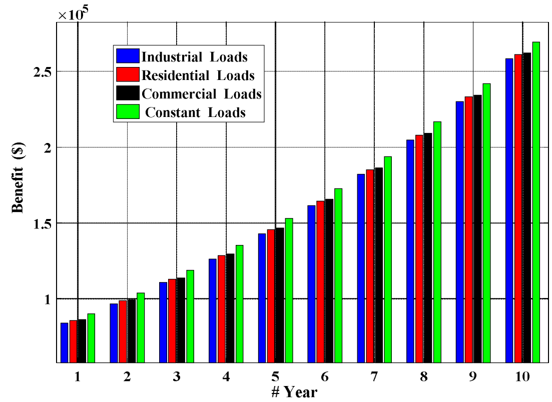

Fig. (8): NPV of constant loads for 10 years

Table (3): The size and location of the capacitor banks obtained for constant loads

NIQP			PSO			TLBO		
# of BUS	Number of Unit Capacitor	Size (kVar)	# of BUS	Number of Unit Capacitor	Size (kVar)	# of BUS	Number of Unit Capacitor	Size (kVar)
3	8	200	3	8	200	3	8	200
5	7	175	4	6	150	4	6	150
7	5	125	5	7	175	5	7	175
9	6	150	9	6	150	9	6	150
11	5	125	11	5	125	15	6	150
16	15	375	15	6	150	16	15	375
17	16	400	16	15	375	17	16	400
18	13	325	17	16	400	18	13	325
19	21	525	18	13	325	19	21	525
20	9	225	19	21	525	20	9	225
21	10	250	20	9	225	21	10	250
22	6	150	21	10	250	25	6	150
29	11	275	29	11	275	29	11	275
SUM	132	3300	SUM	133	3325	SUM	134	3350

Table (4): Summarized simulation results for constant loads

Explanation	**Before Capacitor Placement**	**After Capacitor Placement**		
		MIQP	**PSO**	**TLBO**
Power losses of the year t=1 (kW)	21.18	3.76	4.01	4.13
Power losses of the year t=10 (kW)	60.48	23.13	23.93	24.12
Minimum voltage (p.u)	0.9740	0.9839	0.9836	0.9843
Costs and Benefits	MIQP	PSO		TLBO
Cost of purchasing and installing ($)	71844.000	723220.000		728000.000
Total raw profits ($)	1695524.395	1661897.598		1651592.842
NPV ($)	977084.395	938677.598		923592.842

Table (5): Summarized simulation results for industrial loads

Explanation	**Before Capacitor Placement**	**After Capacitor Placement**		
		MIQP	**PSO**	**TLBO**
Power losses of the year t=1 (kW)	20.33	4.00	4.18	4.36
Power losses of the year t=10 (kW)	58.04	22.18	22.63	23.02
Minimum voltage (p.u)	0.9752	0.9839	0.9838	0.9844
Costs and Benefits	MIQP	PSO		TLBO
Cost of purchasing and installing ($)	71844.000	723220.000		728000.000
Total raw profits ($)	1596983.962	1575956.502		1557929.981
NPV ($)	878543.962	852736.502		829929.981

Table (6): Summarized simulation results for residential loads

Explanation	**Before Capacitor Placement**	**After Capacitor Placement**		
		MIQP	**PSO**	**TLBO**
Power losses of the year t=1 (kW)	20.54	3.92	4.12	4.28
Power losses of the year t=10 (kW)	58.65	22.41	22.95	23.29
Minimum voltage (p.u)	0.9752	0.9841	0.9839	0.9846
Costs and Benefits	MIQP	PSO		TLBO
Cost of purchasing and installing ($)	71844.000	723220.000		728000.000
Total raw profits ($)	1622967.202	1598335.895		1582588.915
NPV ($)	904527.202	875115.895		854588.915

Table (7): Summarized simulation results for commercial loads

Explanation	**Before Capacitor Placement**	**After Capacitor Placement**		
		MIQP	**PSO**	**TLBO**
Power losses of the year t=1 (kW)	20.63	3.89	4.10	4.26
Power losses of the year t=10 (kW)	58.89	22.50	23.03	23.40
Minimum voltage (p.u)	0.9753	0.9842	0.9841	0.9847
Costs and Benefits	MIQP	PSO		TLBO
Cost of purchasing and installing ($)	71844.000	723220.000		728000.000
Total raw profits ($)	1632924.858	1606987.839		1592049.471
NPV ($)	914484.858	883767.839		864049.471

Appendix 1

Parameters of all transformers in the studied network

# of BUS	Peak Load		Bottom Load		R (p.u)	X (p.u)
	P (kW)	Q (kVar)	P (kW)	Q (kVar)		
2	19	11.7	8	2.6	0.71875	0.06
3	409.1	254.2	50.8	37.2	1.28	0.06
4	260.9	203	82.2	65.2	0.71875	0.06
5	547.7	243.3	37.7	30.2	0.71875	0.06
6	185.4	153.4	14.2	12.6	0.71875	0.06
7	260.1	146.1	19.7	15.6	1.839254	0.04
8	445.1	157.4	183.7	99.5	1.28	0.06
9	493.1	203	190.2	83.7	1.28	0.06
10	186.3	67.7	68	26.9	1.28	0.06
11	342.8	149.3	114.8	55.4	1.839254	0.04
12	319.8	113.1	93.2	24.2	1.839254	0.04
13	68.2	21.9	31.5	9.9	1.28	0.06
14	244.2	87	116.3	42.3	1.28	0.06
15	499.4	196.5	445.8	168.9	0.71875	0.06
16	717.5	406.1	439.6	212.2	0.71875	0.06
17	659.5	431.7	389.8	212.2	0.71875	0.06
18	765.6	348.4	304.7	158.7	0.71875	0.06
19	873.5	551.9	306.2	214.9	0.71875	0.06
20	830.5	253	456.2	154.1	0.71875	0.06
21	988	280.5	410.2	119.5	0.71875	0.06
22	346.6	163	101.3	64.7	1.28	0.06
23	138.8	45.9	62.9	20.3	1.839254	0.04
24	183	41.2	55.7	11.1	1.839254	0.04
25	839.6	190.7	267.9	64.2	0.71875	0.06
26	13.9	4.3	5.1	1.2	0.71875	0.06
27	112.5	14	62.6	5.6	1.28	0.06
28	86.1	16.2	8.5	3	1.28	0.06
29	774.6	358.1	81.5	44.9	0.71875	0.06
30	461.1	175.8	53.1	11.2	0.71875	0.06
31	242.2	59.5	125.7	40.6	0.71875	0.06
32	48.1	0.1	66.3	3	1.839254	0.04
33	348.2	106.7	140.3	52.4	1.28	0.06
34	0.7	0.8	0.5	0.6	1.28	0.06
35	394.8	126.6	111.7	65.5	1.28	0.06
Total	13106	5582.1	4906.0	2257.6		

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