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Optimization of Nonlinear Systems for Determining the Type of Conductors in the Network and How to Select the Cross-Section of Conductors in Distribution Lines with the Presence of Nonlinear Loads

Meysam Saeedi Rad[1], Esmail Rok Rok[2]
[1]Ph.D., Department of Electrical Engineering, Islamic Azad University, Khorramabad, Lorestan, Iran
[2]Assistant Professor, Faculty of Engineering, Lorestan University, Khorramabad, Iran
([1]Saidi.meysam93@gmail.com, [2]esmaeel.rokrok@gmail.com)

Abstract- Considering the importance of economic decline of losses, a lot of researches about its optimization with the presence of harmonics in the system have been carried out to determine the optimal amount and placement of capacitive banks and how to choose the type and the cross-section of conductors in radial distribution lines in the presence of linear and nonlinear loads simultaneously to solve this problem and to improve the voltage profile in radial distribution networks, in which all the cases mentioned in this paper, has not been considered in previous studies. To this end, an intelligent nonlinear method is presented for solving the problem and the results are compared and reviewed for several sample networks in different states. This method is based on optimization of the objective function and estimating the constraints resulting from limiting the power quality parameters to the permitted levels, determines the optimum capacity and placement of capacitor banks as well as the determination of the types of conductors in the network, taking into account the effects of nonlinear loads. The objective function includes the economic value of the power losses and the cost of capacitors and conductors selected with constraints such as voltage limitation, the maximum allowable current passing through conductors, the total allowable harmonic distortion, capacitors' capacity, and available and usable conductors. Capacitors and conductors are considered as discrete parameters in this method and due to the low convergence time in the genetic optimization algorithm, this algorithm has been used to solve this optimization problem. The economic loss-optimization software has been written and tested on two sample radial distribution networks in which results show the efficiency of the method and the reduction of losses along with the reduction of the economic cost.

Keywords- *Nonlinear Systems, Optimization Algorithms, Constraints, Capacitive Banks*

I. INTRODUCTION

In order to achieve the objectives of the paper, the structure of this paper is set to firstly review the harmonics and their effect on distribution networks, as well as reduction of losses by relying on harmonic effects. The Capacitor placement method and optimal conductor selection while considering the effect of nonlinear loads will also be explained.

In the following, how to model distribution systems in the presence of linear and nonlinear loads (at basic and harmonic frequencies) for its application in the harmonic load distribution is investigated. Then, a load distribution algorithm based on the forward/backward sweep method is presented, taking into account the harmonic flows which are injected to the network in each Busbar. This algorithm will be used to calculate optimization of losses in the presence of nonlinear loads of the radial distribution system. The computerized optimization program is run on two sample networks. This optimization takes place in two modes, regardless of the harmonic effect and the other, taking into account the effects of nonlinear loads. In each of these modes, optimization is done either by optimal capacitor placement methods or by selecting the optimal conductor or combination of both. The final results of the economic loss reduction optimization program are presented in tables for comparison and evaluation in different optimization modes. Simulation is done on two sample networks with the specified characteristics before optimization and after implementation of optimization in two states regardless of the effect of nonlinear loads and taking into account their effect, and the results are presented. In this paper, optimization for different states is done with the assumption that all loads are linear or have a linear combination and nonlinearity of the loads by either capacitive or conductive or both methods simultaneously on each network, so that the results can be compared with each other and the effectiveness of all modes can be shown. It should be noted that in all simulations and for all networks in this paper, the value of the electric energy losses is considered equal to the value without its subsidy in Iran in 2007. This value, which is indicated by K_p in the objective function of the economic optimization of losses, is set at 770 Rials per kilowatt-hour (equivalent to its annual value of 6745200 Rials per kilowatt), and is a bit cheaper than the value of losses in the US in 2007 which is $ 0.12 per kilowatt-hour. The value of the dollar in this paper is considered 9500 Rials, which is in line with its current price in Iran.

A. *Optimal selection of transmission and Super distribution network conductors to reduce losses*

Optimal choice of conductor type and its cross section in designing and optimizing distribution systems is also an important topic in designing these systems. There are various methods for economic analysis of projects and the selection of the most economical option [7, 21]. The most common way is to use the engineering economic analysis. This method is not very effective in cases such as determining the cross-section of cables while the load combination and the conditions are unclear [21, 22].

The energy of losses that is converted to heat through the cable is divided into two parts. The first part of the losses depends on the flow and as their name suggests, they include any loss of flow, such as losses of phase conductors of the cable and losses due to vortex currents in sheath and metal non-magnetic protectors and hysteresis losses of protectors and magnetic tubes.

B. *Harmonics and nonlinear loads*

One of the issues and problems of power quality in distribution and transmission systems is the issue of harmonics, which has attracted a lot of attention so that many articles can be found in various books and papers. Edward Owen, in 1998, published a history about harmonics in the power grid. He described the experience of the Hartford city of America in 1893 as the first harmonic distortion problem, and that power engineers were faced with an overheating problem of an electric motor and its insulating failure. It must be noted that this motor was tested in the manufacturer's factory and worked well before it was shipped to Hartford. The only difference between the test conditions in the factory and the actual working conditions in Hartford was a 10-mile transmission line. In order to find the reason for this problem, the harmonic analysis was carried out on the waveforms of current and voltage of the transmission line that fed the motor. The results indicate that the warming of the motor was caused by the resonance generated in the transmission line due to the presence of harmonics. It is worth noting that the manufacturers of electrical equipment in Europe, unlike the Americans, were not faced with the escalation of the transmission line until that time because they had not used high frequencies (such as 125, 133, or 140 Hz) in their transmission systems [23]. Harmonic distortions cause certain problems in power networks. Among these problems, the lack of proper operation of the equipment, Loss of life and lowering the efficiency of devices can be mentioned. In this case, harmonic study and a series of rules and regulations will be inevitable. Limiting the harmonic distortion both in terms of electricity companies and in terms of subscribers is necessary. Electricity companies assume that the sinusoidal voltage waveform generated in electric power plants is without harmonics. In most cases, voltage distortion in transmission systems is less than 1%. However, the closer we get to the subscribers, the harmonic distortion will increase. On the other hand, in some loads, the current waveform is completely out of sinusoidal mode and has a large distortion. Although in some cases distortion in the system is random, most distortions are periodic. That is, consecutive cycles are almost similar and may change slowly. In essence, this concept describes the same harmonic term [24, 25]. Today, the use of rectifiers and converters in the industry is very common, and these types of loads form a large part of a power system. The use of rectifiers and inverters has many advantages, but they also have a detrimental effect on the quality of the power. Rectifiers are harmonic generators in the system.

1) *Harmonic distortion*

Harmonic distortion in the power network is due to nonlinear loads. In such elements, the current is not proportional to the voltage applied. In general, the harmonics of each waveform are placed in one of the following four categories [26]:

1. Harmonics: Contain components of the frequency $f = h * f_1$, where h is an integer greater than zero.

2. DC: Component having zero frequency.

3. Inter harmonics: Contain components of $f \neq h * f_1$ where h is an integer greater than zero.

4. Sub-harmonics: contain components with $f < f_1$ and $f > 0$.

In all of the above definitions, f_1 is the main frequency of the power network (50 or 60 Hz). Each periodic distortion wave can be expressed as sum of sinusoidal waves . That is, when the shape of the wave does not change from one cycle to another, this wave can be represented as a sum of pure sinus waves, in which the frequency of each wave is the integer coefficient of the main frequency of the distortion wave. These sinusoidal waves whose frequencies are the integer coefficient of the main frequency are called the main component harmonics. The sum of these sinuses is known as the Fourier series, because this mathematical concept was first taken into consideration by Fourier, a French mathematician. Usually, the harmonics amplitude of high ranks (above 50th) in power systems is negligible. Of course these harmonics can cause malfunctions in low-power electrical devices, but usually do not damage the power systems [24 and 25].

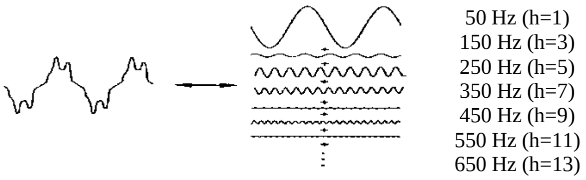

Figure 1. Periodic waveform analysis to sinusoidal waves [24, 25].

2) *Harmonic Generation Sources*

The voltage and current harmonics of the power system are due to the nonlinear characteristics of the specific loads in the system. AC / DC static converters play a large part in generating harmonic currents and distortion in the waveforms of voltage and current in industrial networks and transmission and distribution systems [26]. Harmonic generation factors include the following [23, 24 and 25]:

- Production of non-sinusoidal waveforms by synchronous machines due to the presence of grooves and the lack of uniform distribution of stator windings
- Lack of uniformity in synchronous machines reluctance
- Non-sinusoidal distribution of magnetic resonance in synchronous machines
- Magnetic flux of transformers
- Nonlinear loads such as welding machines
- Electric and induction arc furnaces
- HVDC systems
- Equipment used in speed controllers of electric machines
- Equipment used in electric transport system such as electric buses and subway
- Connecting solar and wind power plants to distribution systems
- Application of SVC as an important tool in controlling the reactive power
- Excessive use of rectifiers for charging batteries
- Industries including chemical and petrochemical complexes, as well as aluminum smelting industries that use high-power rectifiers to generate DC power for chemical processes and aluminum smelting.
- Discharge lamps, especially fluorescent lamps
- Frequency converters
- Switching power supplies
- TV receivers

3) *Philosophy of determining the limitations [26]*

The philosophy of standard harmonics limitation is in two different categories. On the one hand, this standard should determine the limits of current harmonics and also the maximum voltage harmonics in each bus. With this philosophy, one can consider the effects of individual loads and harmonic cumulative effects. On the other hand, the standard should take into account the public interest, both from a user point of view and from the point of view of electricity companies. In other words, since the complete elimination of harmonics is not feasible, in fact, there must be a balance between economic factors and the reduction of harmonics. In the standard prepared by Niroo Consulting Engineers, it has been attempted to determine the exact limits for harmonic indices in each bus so that the harmonic effects in the rest of the buses are within acceptable range. These indices have been determined to be proportional to the effects of harmonics. On the other hand, measurement of indicators should be easily feasible. According to the aforementioned, a number of different items have been proposed in the standard provided that is approved. It has been suggested in this standard that, due to the complexity of harmonic production and the accumulated effects of different loads, harmonic computerized studies and harmonic measurements take place in different time periods. On the other hand, studies by large consumers who produce harmonics are required to determine the internal state of the system as well as the impact on the distribution network. These studies should generally be carried out in conjunction with the harmonic output of various equipment and the possibility of resonance in the system. In determining the permissible values for voltage and current distortion, it is necessary to consider the lack of synchronization between the factors creating the harmonic current. This lack of synchronization is determined from two different perspectives: Time difference in generating harmonic values of each user and the other, the phase difference between the simultaneous harmonics produced by different equipment. Another suggestion of this standard is that if the harmonic current of each user falls below the limit set by the standard, but the allowable values of the voltage harmonics are not met, it is necessary to coordination between the users and the electricity companies to provide suitable conditions by having some arrangements, such as using a filter or displacement of capacitor in different buses.

4) *Total Harmonic Distortion Coefficient Index (THD)*

There are several numerical criteria for showing the harmonic values of a wave. One of the most famous ones is the total harmonic distortion (THD) according to equation (1), which can be calculated for the voltage and current.

$$THD = \frac{\sqrt{\sum_{h=2}^{h_{max}} M_h^2}}{M_1} \tag{1}$$

Where M_h is the effective value of the h (th) harmonic component. The THD index is the measurement criterion of the effective value of the harmonic component in a distortion wave [24, 25]. For most applications, it is sufficient to consider the range of harmonics from step 2 to 25. Of course, most standards consider up to step 50 [27]. As we know, the total effective value of a wave (RMS) is not equal to the sum of its components, but is obtained from the square of total squares of each component of that wave. The THD can be related to the effective value of the waveform using the equation (2-2).

$$RMS = \sqrt{\sum_{h=1}^{h_{max}} M_h^2} = M_1\sqrt{1+(THD)^2} \tag{2}$$

The THD index is a useful quantity for many applications however, its limitations should also be considered. This quantity can provide a good idea of the excess heat generated in a resistive load when the distortion voltage is applied to it. It can also be a sign for additional losses due to the current flows through a conductor [24, 25]. One of the disadvantages of this index is the lack of harmonics order in computing it [28].

5) *Harmonics Control*

When a harmonic problem occurs in the network, the main methods of controlling the harmonics are as follows [24, 25]:

- Reducing the amount of harmonic currents generated by the load: for example, one can remove a transformer from saturation and then from harmonic generating by reducing the applied voltage. Also, by adding series reactor in line, you can reduce the harmonics generated by some power electronic converters. Connection type of transformer can also be used to reduce harmonics in a three-phase system.

- Adding a filter to create a path for harmonics or prevent harmonics from entering the network: parallel filters reduce the distortion by short cutting the harmonic current. Series filters also block the current harmonics. Active filters also perform harmonic elimination by entering current harmonic components into a nonlinear load.

- Changing the frequency response of the system using a filter, reactor, inductor and capacitor.

6) The effect of harmonic distortion on equipment performance and power system

Harmonic distortions are injected into the rest of the network as harmonic currents by nonlinear loads, and according to the network impedance, are applied to different equipment as harmonic voltage distortions. Therefore, equipment used in harmonic-contaminated power networks are permanently exposed to these distortions [26]. Some of the bad effects of harmonics on the power system and its equipment are as follows [24, 25]:

- Failure of capacitor banks due to insulation fault or excessive increase of reactive power.

- Insulation failure of the cables due to the harmonic overvoltage in the system

- Interference with RIP control systems and interference in the remote control function of keying and measurement systems.

- Additional Ohmic losses, as well as additional losses in the core and high temperatures in electric machines

- Interference with telecommunication systems and PLCs

- Error in measuring devices

- Mechanical fluctuations

- Inappropriate performance of controlling systems

- Inappropriate performance and wrong relay response

- Inappropriate performance of fire circuits of power electronic systems

C. Optimal reduction of losses by relying on harmonics

Reduction of losses in distribution systems which include the highest losses is carried out in a variety of ways, one of which is the optimal capacitor placement and the other is the optimal selection of conductors in these systems which were explained in the first chapter. Several papers on each of these methods have been presented, but none of these methods have been used simultaneously to optimize the economic loss of the distribution system. Therefore, it can be claimed that these two methods haven't been used simultaneously for optimization purpose so far in the presence of nonlinear loads in the power system. Here, the history of each of these methods and how they are implemented in distribution systems and their type of optimization will be explained separately.

1) Optimal reduction of losses by capacitor placement based on harmonics

Today, due to the development of nonlinear loads, harmonic distortions are applied to the rest of the network by these loads, and according to the network impedance, they are applied as harmonic voltage distortions to the equipment. Harmonic contamination caused by several nonlinear loads such as diode or thyristor rectifiers, speed regulators for electric motors, cyclo-converters and etc., is also causing several problems in the network. The undesirable effects of current and voltage harmonics on the power system and equipment are significant. These effects include additional heat in equipment, insulation problems, and inappropriate performance of measuring and protection devices such as relays, fuses, and etc. Many efforts are made to clean the system from harmonics and increase power quality. Such efforts include the installation of various tools for the removal of harmonics, such as passive and active filters, Unified Power Quality Conditioners (UPQC), or Active Power Line Conditioners (APLC). With the help of these tools, the voltage and current harmonics are kept within the permissible limits set by the standards. The most important equipment affected by this harmonic contamination is the capacitors used in the network. Although capacitors are devices that do not produce harmonics themselves, they affect the existing harmonics due to nonlinear loads which requires to be studied. The first effect of the capacitance is to distort the current harmonic from the main path, that is, from the harmonic source to the network, and the other effect is that it can cause resonance in the natural frequency of the system. The voltage harmonic causes the capacitor to operate with a current and voltage that is proportional to the harmonic frequency. Capacitors are not harmonic generators, but the use of a capacitor in networks that have a current or voltage harmonic triggers resonance in the power grid. Capacitive reactance decreases with increase in frequency, and inductive reactance increases with increase in frequency. As a result, resonance occurs at a certain frequency. When the resonance phenomenon (LC series or parallel circuit) occurs, the amplitude of inductor current or the capacitor voltage may be very high. The use of capacitor in distribution networks is generally, as stated, to correct the power factor and voltage stability, and both types of series or parallel couplings of capacitors or a combination of them may be available. In the case of a series circuit, at the resonance frequency, the total impedance of the network decreases to the impedance of the resistance in the circuit, and if this resistant component is small, very high currents will pass through the circuit. In parallel circuits, the resonance frequency of the total impedance of the network is very high. As a result (due to a very small stimulation), a large spin current passes between the inductor and the capacitor, and the voltage of the network becomes very high. Therefore, if the resonance frequency of the network is close to one of the harmonics created in the circuit, very large currents or voltages are generated in a harmonic network, which as it was said, causes failure in capacitor bank, incorrect and repeated operation of capacitor fuses and insulation failure in cables [23]. It can be seen that with the proper selection of capacitor banks, harmonic levels can also be controlled. Of course, this does not mean that it is always possible to only improve the quality of power in networks with high harmonic pollution to a standard level by placing capacitor banks, but depending on the circuit topology and the linear and nonlinear loads, the power quality of the network can be improved. In some networks, harmonics may be reduced to acceptable levels by placing capacitor banks or other tools might be needed to restrict them. In view of the above, we find that the optimal choice of the size and location of capacitor banks is one of the important issues in the network. The proper choice of capacitor banks can lead to limiting losses and as a result cost reduction in the system, as well as placing constraints on the amount of harmonics. Paying no attention to the presence of harmonics in determining the optimal size and location of capacitor banks not only can result in failure to achieve optimal response in real conditions, but may also increase the amount of harmonics or the occurrence of resonance in some harmonic frequencies. In summary, by locating the capacitors appropriately from the installing location and size point of view, the resonance can be transferred to non-destructive frequencies. For this purpose, it is necessary to apply optimal selection and placement of capacitor banks taking into account the harmonic levels of buses one at a time. Most capacitor placement techniques are done by assuming sinusoidal conditions and regardless of the effect of harmonics [29, 30 and 31]. Limited research has been done considering the effect of harmonics on radial system losses for optimal capacitor placement, and in most of them only the input voltage of the network is assumed to be nonlinear [32, 33]. The capacitor placement actually consists of determining the optimal number, type, location and size of the capacitor banks in such a way that the lowest annual economic cost can be obtained in terms of power loss, energy and the cost of capacitors, while the power quality and setup constraints also occur in allowed and required system limits. There have been many articles in this field that can be categorized into several categories according to the type of problem solving methods used to optimally place capacitors in distribution systems. Of these methods are the initial analytical method, numerical programming method, intelligent methods, a method based on algorithms such as genetics, melting of metals, artificial intelligence networks, fuzzy theory, group intelligence, or ants. Reference [34] has provided all of these methods and their application rates in papers to solve the optimal capacitor placement problem from the beginning to the year 2000. In most capacitor placement techniques which are done assuming sinusoidal conditions and ignoring the effect of harmonics and in fact eliminating the effect of nonlinear loads, it is assumed that all of the loads in the system are linear. Their problem solving methods are mostly like those used in the reference [34]. Some papers that have involved harmonic computations in solving the problem of optimal placement of capacitors, have selected the optimal capacitors in a variety of ways, such as the universal search method [35], local variables [36], maximum selectivity of sensitivity [37], the combination of nonlinear and numerical programming [38] or an intelligent method [39]. In these articles, the limitations of power quality have been added in different ways in solving the objective function and its optimization in addition to other constraints. In some of these papers, such as [39,37,35], the objective function is considered as the primary criterion for capacitor placement, and the constraints and power quality limitations are considered after optimization, which can be one of the main disadvantages of this solving method in these papers. In [38], the cost function and the constraints function are not properly combined, which results in a poor optimal answer point. In [40], genetic algorithm is used for the optimal placement of a capacitor in a 10-bus non-subtractive radial system and the effect of nonlinear loads is well considered within it, but the Newton-Raphson method for load distribution has been used to solve the problem which is incorrect because the load in this radial network will not converge. The answers of this paper are completely incompatible with the answer of Mr. Baghzouz, who simulates the same network in a harmonic environment using local variables [36]. Paper [32] solves the problem of optimal capacitor placement and determining its optimal value in the presence of harmonics by fuzzy method and compares the advantage of this method with the proposed algorithms in other papers. Paper [41] acts as [40], but in this paper, only the main input bus of the network generates harmonic and the rest of the loads is assumed linear. In this paper, the BPSO algorithm or Binary Particle Swarm Optimization is used. The objective function in this paper is the cost of installed capacitors and network losses. In this paper, the advantage of the BPSO optimization method is compared with another intelligent method and the genetic algorithm method from other papers for the same network. In [40], this method was implemented on a completely radial distribution feeder as presented in [41, 36], which, of course, did not provide a better answer than the genetic optimization algorithm, but only its convergence speed increased a little.

2) Reducing the optimal loss by determining the cross-section and the placement of conductor based on harmonics

The effects of harmonics on conductors can be divided into several stages in this section:

1) Increased electrical tension and losses in conductor insulations

2) Varying the electrical parameters of the lines

3) Increasing the effective current of the line and changing its power factor

4) Occupying a part of the capacity of the lines by the non-useful powers created by the harmonics

5) Increasing copper losses in conductors

As already mentioned the presence of harmonics increases electrical tension and also increases dielectric losses in insulators. It is worth noting that each of these two factors can potentially affect the ability of the insulation and lead to its failure. Due to the fact that there are insulators (solid, liquid and gas) in all equipment used in the electrical industry, it is necessary to study the effect of harmonics on insulators. One of this equipment is ground cables, which harmonics can seriously affect their insulation performance. Also, non-useful powers from the harmonic effects can occupy some of the capacity of the lines or conductors. The harmonics affect the electrical parameters of the lines and increase the effective current of the entire line, which reduces the transmission capacity of the line. In 1927, Constantian I. Budeanu obtained a mathematical model for the apparent capacity of lines known as the Budeanu model. In this model, the apparent capacity of the line is divided into three active, reactive and distortive components according to (3) [42, 43 and 44].

$$S = V_{rms}\, I_{rms} = \sqrt{P^2 + Q^2 + D^2} \qquad (3)$$

In this equation, P, Q, and D show active, reactive and distortive powers, respectively. So, S represents the capacity needed to transfer power from the lines. Distortion creates additional current components in power networks; therefore the capacity needed to transfer the load power in the line gets larger. Since the line must transfer the main load power in addition to the distortion (harmonic) power, thus the apparent capacity of relation (3) can be simplified into two main and harmonic sections as in equations (4) and (5):

$$S^2 = (V_1 I_1)^2 + (V_1 I_h)^2 + (V_h I_1)^2 + (V_h I_h)^2 \qquad (4)$$

$$S^2 = S_1^2 + S_h^2 \qquad (5)$$

In the above relations, V_1 and I_1 are the voltage and current values in the main frequency, and V_h and I_h are the voltage and current values, in the h-th harmonic component, respectively. S_1 is the main apparent capacity of the line and S_h is its harmonic apparent capacity. The relation between S_1 and S_h is as (6) according to the mentioned relations.

$$\left(\frac{S_h}{S_1}\right)^2 = THD_i^2 + THD_v^2 + (THD_i \,.\, THD_v)^2 \qquad (6)$$

In this equation, THDi and THDv are the total harmonic distortion of the voltage and current, respectively. Considering the prior assumptions with the sinusoidal voltage source, the above relation is simplified as in (7) with a low error rate.

$$\frac{S_h}{S_1} = THD_i \qquad (7)$$

According to Equation (7), the ratio of the capacity occupied by the harmonics to the main load power is proportional to the total harmonic distortion of the current. Therefore, with increasing distortion, a larger share of the capacity of the lines is occupied by non-useful power. It should be noted that the determination of the cross-section of cables and conductors should be considered from the technical and economical point of view. However, cable design is often limited to only technical issues (maximum current and allowed voltage drop) but engineer designers should provide the most economical plan for cable installations in addition to technical issues. There are various methods for economic analysis of projects and the selection of the most economical option. Several articles have been published in these fields. Most of these articles have solved the problem of selecting the optimal conductor in the linear load conditions of the system [45, 46, and 47]. In [45], an algorithm for selecting the optimal conductor in radial distribution systems has been proposed, through which, in addition to obtaining the type and size of the cable, the best economic option is also obtained for installation in the distribution system. In this method, by using the new load distribution method formulated in this paper, the losses in the whole network are reduced in addition to the optimal and economic selection of the conductor in the network. In this paper, this method is implemented on a 32-bus network and its results are presented. In a small number of papers, the optimal conductor selection has been made taking into account the harmonic effect of the loads including the paper [22, 48]. The decision theory is one of the issues that have been growing very rapidly over the last two decades, especially in the economy and business. The paper [22] describes the method of determining the optimal cross-section of medium-voltage cables with nonlinear loads under uncertain conditions using the decision theory. For this purpose, this paper describes how to determine the total cost of cable in non-sinusoidal conditions and how to form a decision matrix, and has used it in determining the optimal cross-section of the cable in a practical sample. Finally it should be noted that, optimization of losses with the presence of a capacitor and a conductor consideration the effect of the harmonics simultaneously has not been done which is used in this project. This chapter will explain this method. In order to perform this optimization, it is necessary to carry out harmonic load distribution on the network. For this purpose, the next chapter, i.e., the third chapter will explain the harmonic load distribution.

3) *Bus sample network*

This sample network is a single-line radial distribution network according to Fig. 1 with 9 buses (m=9) assuming a base frequency of 50 Hz and a 20 kv voltage. The load information of this network is presented in [40].

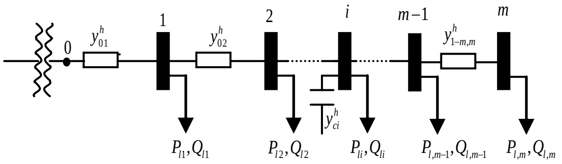

Figure 2. A single-line diagram of a 10-bus sample system [36, 40, 41]

TABLE I. THE CHARACTERISTIC OF 3-PHASE LOADS AND ITS NON-LINEAR PERCENTAGE IN THE 10-BUS SYSTEM [40]

Load nonlinearity (%)	Q (kvar)	P (kw)	Bus No.
0	460	1840	1
55.7	340	980	2
18.9	446	1790	3
92.1	1840	1598	4
4.7	600	1610	5
1.9	110	780	6
38.2	60	1150	7
4.5	130	980	8
4.0	200	1640	9

The first column on the right shows the nonlinear load percentage on each bus. The type of load considered in bus No. 1 in the network is linear and the rest is a combination of linear and nonlinear loads.

4) *Before Optimization (item 1)*

In this section, the load distribution on the existing 10-bus network has been made with the specified specifications. The load distribution has been carried out in a forward-backward sweep method. By doing this, the values of voltages in each bus and the total amount of active power losses before the optimization are determined on the grid. The type of conductors and the voltage values for each bus before the optimization is shown in Mode 1. It should be noted that all voltages in all tables correspond to the last bus. The maximum and minimum voltages, the total active power losses of the system, the value of conductors in the network, and the economic value of system losses in the first state is given in in Mode 1 before the optimization to compare with those of the next mode. In this case, it is observed that the maximum value of the voltage is 0.9 and its minimum value is about 0.77 Per-units. The voltage of 0.77 Per-units in the distribution system is low and unacceptable.

5) *Backward-Forward Sweep Method in radial load flow and its development in radial distribution networks with harmonic loads*

In order to carry out the load flow in power networks, it is necessary to solve a series of nonlinear equations using some numerical methods such as the Newton-Raphson method. In radial distribution networks, a simpler way is used for load flow due to its specific features. This method is generally used to calculate the load flow in distribution networks. Since nonlinear loads in power systems are increasing, and in some operations and planning it is necessary to perform more precise load flow and more accurate calculation of losses in distribution networks, calculations should consider different harmonic relations and voltages related to these harmonics must be calculated.

In this section, a load-flow algorithm based on the Backward-Forward Sweep method is presented, taking into account the harmonic currents injected into the network in each bus [51, 52]. In this proposed method, the elements and equipment of distribution network (such as transformer, cable, etc.) are modeled for different harmonics, and through performing some voltage calculations, different harmonics and THDs per bus is calculated. Also in this method, according to the type of three-phase coupling of distribution transformer in each bus, transmission or non-transmission of harmonic currents of the third order is considered. This method has been tested for the IEEE 37-bus network and the results show the efficiency of the proposed method.

6) *After Optimization*

a) *Optimization by determining the optimal location and optimal amount of capacitor banks (item 2)*

In this case, optimization is performed on the 10-bus network through optimal placement of the available capacitor banks. In this case, after executing the program on the network, the value of capacitor banks and their location are determined in such a way that simultaneously with the significant reduction of losses in the whole system, the total annual system cost and voltage values will also be improved. In fact, by implementing this method, we will achieve an economic decline of losses.

b) *optimization with optimal selection of conductors (item 3)*

In this case of the economic optimization of losses, the optimal type of conductors installed on the network is determined to reduce the economic loss associated with the improvement of the voltage profile. This selection should be made in such a way that, in addition to the economic decline of losses, the total annual cost of the system and the voltage status of the network buses also improve. In the implementation of this program, it should be noted that the current of lines should not exceed the allowable current of conductors. Therefore, objective function of economic optimization of losses in this case includes the allowed range of network voltage and the maximum allowable current of selected conductors.

In order to establish the optimization constraint, as in Mode 2, the maximum and minimum range of the voltages is considered to be 1.02 and 0.9 per-units, respectively. In fact with this constraint, the voltage value of network buses should not exceed these limitations by the implementation of optimization program on the system. The limit for the maximum allowable current of selective conductors is also given in Table (1). The conductors intended for this network are selected from Table (1).

This program is implemented on the 10-bus network and its results in state 3 are presented in the and for comparison. It can be seen that after optimal conductor placement, more loss reduction is obtained compared to optimal capacitor placement in the grid, but the overall cost of the system in addition to the high value of conductors is more than optimal capacitor placement, which is due to the introduction of a voltage constraint in determining the type of network conductors. If this constraint is removed from the problem, a very significant economic decline will be achieved by selecting the optimal conductors, which due to the comparison in the same condition between states, this voltage is not ignored. The rate of system losses improvement in this case compared to mode 1 (before optimization) is equal to 154.5 kw, which is 10.3 in percent. In this case, the economic cost of the whole system will be 12.931 million Rials, which has improved by 98 million Rials compared to Mode 1.

c) *Optimization with optimal capacitor placement and optimal selection of conductors (item 4).*

In this section, the optimization program operates in such a way that in addition to the capacitor placement, the optimal type of the system conductors is also determined. In this case, the discrete values of the capacitor banks as well as the type of network conductors should be selected together in such a way that in addition to reducing losses, the economic cost of the system and the voltage profile of network buses improve. In solving the problem of economic optimization of losses in this case, the cost of capacitors and conductors, as well as the annual economic value of losses are considered.

TABLE II. RESULTS BEFORE AND AFTER OPTIMIZATION IN A 10-BUS NETWORK, WHERE ALL LOADS ARE LINEAR.

			Before optimization		After optimization						
			Mode 1		Mode 2 Capacitor Placement		Mode 3 Conductor Placement		Mode 4 Capacitor and Conductor Placement		
Line No.	First Bus	Last Bus	Conductor type	Voltage (p.u.)	Capacitance (kvar)	Voltage (p.u.)	Conductor type	Voltage (p.u.)	Capacitance (kvar)	Conductor type	Voltage (p.u.)
1	1	2	--	0.9900	1800	1.0017	--	0.9903	450	--	0.9986
2	2	3	--	0.9821	1050	1.0083	--	0.9826	1350	--	1.0026
3	3	4	1	0.9500	1800	1.0001	1	0.9515	900	1	0.9891
4	4	5	2	0.9282	1800	0.9901	1	0.9374	2250	1	0.9834
5	5	6	2	0.8843	1200	0.9715	1	0.9108	1050	3	0.9574
6	6	7	2	0.8700	1200	0.9662	3	0.9105	450	3	0.9488
7	7	8	4	0.8439	150	0.9505	3	0.9075	450	3	0.9390
8	8	9	4	0.8004	1500	0.9293	3	0.9043	150	3	0.9227
9	9	10	4	0.7698	750	0.9097	4	0.9001	900	4	0.9042

After performing the loss optimization program on the network in Mode 4, the capacitor values, the type of conductors and their location in the network are determined. These values and their location, as well as voltage values in each bus, are given in shows that in mode 4, like in modes 2 and 3, the voltages are within their permissible range, and the permissible current limits for conductors are also observed. The annual economic cost of the network in Mode 4 is equal to 11466 million Rials, which has improved by 1563 million Rials compared to the pre-optimization mode. The improvement percentage of this annual economic cost of the network is 12%, which is a significant amount, because in addition to a 12% reduction in the annual cost of the system, the power loss was also reduced by 19.4%, and at the same time, the voltage values of the buses have improved.

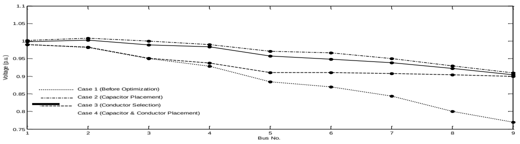

Figure 3. The comparison of the sample network bus voltages in 4 states

It can be seen that in the case of optimization with the combination of two optimal capacitor and conductor placement methods in the system, both the reduction of losses and the economic reduction of the annual cost of the system are much more significant than those that each of these methods were separately run on the system.

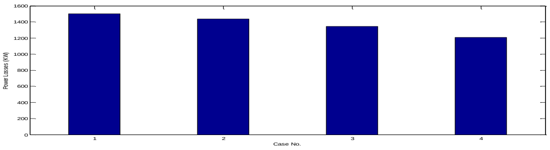

Figure 4. The losses of a 10-bus sample network in different modes of optimization and before that.

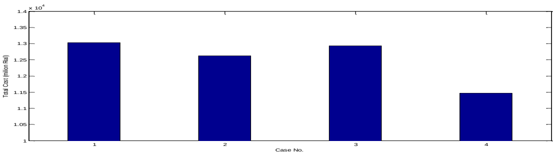

Figure 5. Comparison of the annual cost of a 10-bus sample network in different modes of optimization and before that.

The diagrams in Figure 2 show that the improvement of the bus voltages is the best in the state of capacitor placement, and then in state 4, i.e. the capacitor placement along with the optimal conductor selection. Although the improvement of the bus voltages in general (Mode 4) is less than that of Mode 2, but according to Figures 3 and 4, the power losses and also the annual system costs are lower than all other modes which is a very important advantage for this method.

In order to compare the superiority of the optimization modes with each other, the percentage of losses improvement and average voltage as well as the annual economic costs of the whole system are presented in Table 3.

D. *The state with considering the effect of nonlinear loads in the 10-bus network*

Due to the inevitable presence of nonlinear loads in distribution systems, it is not possible to ignore the harmonic effect of these loads on the distribution system equipment, especially conductors and network capacitors. Therefore, it is necessary to have the optimization by optimal capacitor or conductor placement or simultaneously together in order to reduce the economic losses, taking into account the effects of these loads on the network. In this section, before any optimization, harmonic load distribution is performed on the sample network and the values of the voltages and main and harmonic losses of the network are presented as the results. After that, the optimization is carried out in two modes: capacitor and conductor placement simultaneously, and capacitor placement separately in the presence of the harmonic components of the network.

1) Before Optimization (item 1)

In this section, the harmonic load distribution on the existing network is done taking into account the effect of nonlinear loads. All obtained values, effective voltages, and the total harmonic distortion (THD) in each bus, as well as the type of system conductors before optimization, are presented in. In this system, total losses before the optimization are 1508.5 kw. In this case, the economic cost of the whole system will increase due to the existence of harmonic losses compared to its non-harmonic state, which is equal to 13085 million Rials in this network.

2) After Optimization

A: Optimization by determining the optimal location and optimal amount of capacitor banks (item 2). In this section, as in section, in order to optimize losses economically, the optimal capacitor placement in the network is used, with the difference that the loads in this system are nonlinear and their effect is also considered. Certainly, due to the presence of harmonics in the network, their optimal location and amount in the network will be different from that of the non-harmonic state. In this case, the permitted voltage range for optimization is considered the same as the state regardless of the harmonic effect. Therefore, the permitted range for the maximum and minimum voltages is 1.02 and 0.9 per-unit, respectively. To establish restrictions on the amount of total harmonic distortion, its maximum allowable value in the network is equal to 5% considering the IEEE standard 519. After the implementation of the optimization program and determining the capacitor values, the effective voltage of the buses is improved and placed within its allowed range, so that the maximum value of the voltage is about 1 per-unit and its minimum value is equal to 0.9001 per-units. In this case, in addition to an improvement of 12% of losses and 9.2% of the total annual economic cost in the system, the total harmonic distortion (THD) would be improved by 44.48% in accordance with the relationship (3), which is a significant amount.

$$THD\ improvement = \frac{9.0068 - 5}{9.0068} = 44.48\% \qquad (8)$$

B. Optimization by optimal capacitor placement and optimal selection of conductors in nonlinear-loaded networks without considering harmonics (item 3)

In this case, nonlinear loads are present in the network, but optimal capacitor and conductor placement in the system is solved without considering their effect. It means that the calculation of harmonic loads is not included in the optimization and the system's objective function. The constraints of the problem will include the two permissible voltage ranges for busses and maximum permissible conductor current, but the maximum total harmonic distortion limit is ignored. By implementing this program on the network, the amount and location of optimal capacitive banks and also the type of optimal network conductors are determined. These values, along with the effective voltage of the buses after optimization, are indicated in Mode 3 in. The values of the main and harmonic voltages and the THD values in each bus of this network are given in terms of per-unit and percentage in. According to the results, it is seen that as a result of this optimization, the amount of losses is lower than all cases. The amount of losses reduction compared to the pre-optimization state (item 1) is 23% which is more than all other cases and also the improvement of the annual economic cost of the whole system compared to the first one, i.e., before optimization is 11% which is a significant amount. The voltages and currents are also within their permissible range due to the fact that they are among the constraints of the optimization problem;. In this case, after implementing the optimization program, the amount and location of the capacitor banks along with the type of system conductors are determined. The results of this optimization in Mode 4 are clearly illustrated in and It can be seen that the voltages are within their permissible range, so that its minimum value is in a very favorable position. In this case, the maximum amount of THD in the network buses is equal to 4.07%, which is acceptable with respect to its maximum allowable value. Meanwhile, both reduction of losses and reduction of the annual economic cost of the system are much more favorable in this state than those of the pre-optimization state and also the optimization by the capacitor placement method, which is due to the effect of the optimal conductor placement coupled with the capacitor placement in the network. The percentage of losses improvement in the system in this case is 16.64% and 5.3% in pre- optimization state and optimization with capacitor placement, respectively. The percentage of annual economic cost improvement for the whole system is 9.9% compared to the pre-optimization state.

TABLE III. THE OVERALL RESULTS BEFORE AND AFTER OPTIMIZATION IN THE 10-BUS NETWORK WITH CONSIDERING THE EFFECT OF NONLINEAR LOADS.

	Before Optimization	After Optimization		
	Mode 1	Mode 2	Mode 3	Mode 4
Maximum effective voltage (p.u.)	0.9900	1.0044	1.0019	1.0074
Minimum effective voltage (p.u.)	0.7729	0.9001	0.9348	0.9470
Average voltage (p.u.)	0.8921	0.9598	0.9700	0.9774
Maximum THD (%)	9.0068	5.0000	7.1482	4.0721
Harmonic Losses (W)	8383.3	10002	13573	5021.0
Losses at the main frequency (kW)	1500.1	1317.5	1148.3	1252.35
Power losses (kW)	1508.5	1327.6	1161.9	1257.37
Total capacitors (kvar)	0	8850	7650	9750
The cost of Conductors (Million Rials)	2910.4	2910.4	3792.5	3293.2
The cost of Capacitors (Million Rials)	0	17.341	15.153	17.834
The cost of annual losses (Million Rials)	10175	8954.6	7837.2	8481.21
Annual cost of the entire system (Million Rials)	13085	11882	11645	11792
Profit earned (Million Rials)	--	1203	1440	1293

Figures (5), (6), (7), (8), and (9) illustrate the comparison of bus voltage, THD values of buses, system losses in different states, the annual cost of the system in different situations and the maximum THD value in different conditions of optimization and before the optimization, respectively. Figure 5 shows that the best condition for improving the bus voltage is related to mode 4, in which capacitor placement and optimal conductor placement in the system is performed simultaneously together by taking into account the harmonic effects in the calculations.

Figure 6 shows that the best condition and actually the least amount of THD is for Mode 4 and its worst value in network buses is in Modes 1 and 3, which has been no control over this criterion.

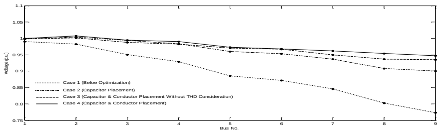

Figure 6. Comparing the voltage of buses in a 10-bus sample system in different states of optimization and before it.

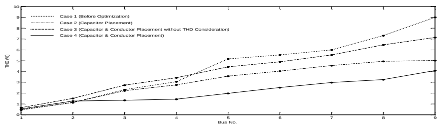

Figure 7. Comparing the THD value in a 10-bus sample system in different states of optimization and before it.

Figure 7 shows that the amount of losses in Mode 3 is lower than all, but this can't be an advantage for this mode because it is clear from Figures 6 and 9 that the harmonic state of the buses is not suitable in this system.

Fig. 8 which shows the annual cost in different situations also shows that it is necessary to pay more to reduce the THD in network buses. In this case, due to the fact that there is no cost to improve this harmonic criterion in Mode 3, so this mode is better in terms of economic cost reduction than Mode 4.

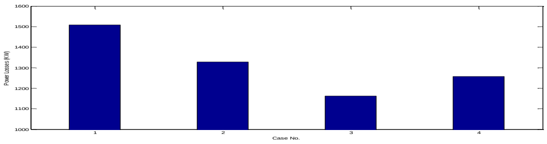

Figure 8. Comparing the losses of a 10-bus sample system in different states of optimization and before it.

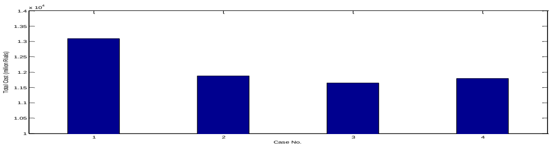

Figure 9. Comparing the annual cost of a 10-bus sample system in different states of optimization and before it.

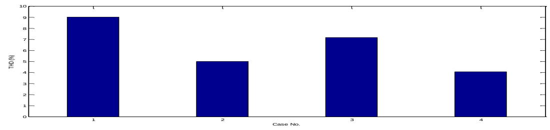

Figure 10. Comparing the maximum THD of a 10-bus sample system in different states of optimization and before it.

The recovery rate of power losses, voltage average, THD and the annual economic cost of the whole system compared to pre-optimization state are presented in two modes of optimization (Mode 3 and 4) in for comparison.

II. CONCLUSION

In this paper, two methods of optimal placement of capacitors and optimal selection of system conductors were considered simultaneously in the presence of nonlinear loads in the network in order to reduce the losses in radial-distributed systems. This optimization and reduction of losses in the system should be done in such a way that:

- The effective voltage of all the system buses shall be within the permissible range.

- Permissible current of the conductors shall not exceed the maximum permitted flow.

- The total harmonic distortion value in each bus, which indicates the amount of harmonic contamination due to nonlinear loads in the system, should not be exceeded from the maximum permissible limit.

- The total annual cost in the system should be reduced.

After simulating the system conditions in a harmonic environment, a computer program of economic optimization of losses was provided to obtain the above conditions in the presence of nonlinear loads and was performed on two sample networks in different scenarios, and the results were shown.

These results showed that in optimizing the losses by optimal selection of conductor and capacitor method in radial distribution systems, the effect of harmonics in the system should also be considered in the calculations, because if it is ignored, although the annual cost of the system decreases better but its harmonic contamination is outside the permissible limits and may cause resonance in the system. Also, the results showed that the method used in this paper, which is a combination of two methods of optimal placement of capacitors and optimal selection of conductors in the presence of nonlinear loads of the system, is better than any of the methods used separately in different situations in terms of reducing losses, as well as reducing the annual cost of the system. In general, the results of this method on sample system showed that by implementing this method, in addition to a significant reduction in losses in the system, the annual cost of the system will decrease, as well as the improvement of the voltage profile of the buses both quantitatively and qualitatively that shows the usefulness of this method in reducing the economic losses of radial distribution systems. The method used in this paper to reduce the losses optimally and economically in radial distribution systems, has not been used so far with combination of optimal capacitor placement and optimal conductor selection. In this paper in addition to perform these two methods simultaneously, the effect of the presence of nonlinear loads was also considered in optimization. Therefore, it is possible to combine the various methods used to reduce the losses in power systems to achieve better and more efficient results in such systems. For example, by combining several important ways to reduce losses, such as optimal conductor selection, optimal capacitor placement, adjusting transformers' tap or their optimal placement, repositioning, optimal placement of FACTS devices, and optimal placement of distributed generation elements in the distribution systems in the presence of nonlinear loads and their non-equilibrium conditions, the most optimal and practical way in reducing economic losses in such systems can be achieved and later the expressed ideas can be presented to improve the system.

1. Economic optimization of losses by capacitor optimal placement and conductor optimal selection simultaneously in unbalanced and nonlinear conditions of loads in the distribution networks.

2. Optimization of losses in distribution systems by capacitor optimal placement, conductor and network re-arrangement simultaneously in the presence of nonlinear loads.

3. Economic optimization of losses by optimal placement of capacitors and transformers and their tap adjustment, optimal conductor selection and network re-arrangement simultaneously in the presence of nonlinear and unbalanced loads in distribution systems.

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Meysam Saeedi Rad, born in Iran in 1988, Khouzestan, Andimeshk, Ph.D. student of Electrical Power Engineering, Islamic Azad University, Khoramabad Branch, Lorestan, Iran. Saeedi Rad, is responsible for the control and tools of the company for exploitation and transportation of water in Ghadir of Khuzestan and lecturer at various universities such as Abadan University, Abadan University of Applied Sciences and Ahwaz Chamran State Technical School. He has authored more than 40 international papers. And author of 5 specialist books in the field of electrical power engineering called Dynamic Foundations and Stability of Power System and Connection of Solar Farms printed in Kharazmi Publications Engineer

Meysam Saeedi Rad is a member of the Iranian Engineers Association and the National Elite Foundation of Iran. He works in various journals such as IEEE as an Arbitrator. In 2015, he was recognized as a researcher at the Free University.