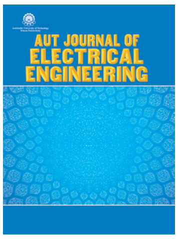

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Probabilistic Optimal Planning of Passive Harmonic Filters in Distributed Networks Considering Possible Network Configurations with High Penetration of Non-linear Loads

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ABSTRACT: Nowadays, non-linear loads are being used in distribution systems increasingly. Despite the good features such as low initial construction cost, high efficiency, and controllability, these loads cause harmonic distortions. In previous studies, passive harmonic filters have been proposed to decrease the produced harmonics, and to do so, various techniques have been suggested. However, the probability of daily load change, possible arrangements of distribution grid taking into consideration the filter design requirements and the impact of temperature change in harmonic filter parameters have been neglected in these studies. Therefore, in the current paper, a comprehensive model based on the probabilistic rearrangement of the distribution grid has been presented for the probabilistic planning of passive harmonic filters. In the proposed method, a two-level probabilistic optimization problem has been introduced with the objective of reducing harmonic distortions, voltage profile improvement, and loss, and investment cost reduction. As a result, the optimum placement of filters, the most optimal number and type of filters, and filter design parameters have been determined. The proposed procedure has been applied to the modified 33-bus IEEE network. The simulation results indicate that neglecting grid rearrangement may lead to a violation of power quality limits during some hours of the day. On the other hand, the combination of various network topologies in planning studies ensures that the total harmonic distortion (THD) level is maintained within the standard range, guaranteeing loss, line density, and filter investment cost reduction.

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1- Introduction

1- 1- Problem Statement and Literature Review

In recent years, distribution grids have been increasingly affected by the random nature of loads and renewable energy sources (RES) such as photovoltaic (PV) systems. On the other hand, distribution system rearrangement which is normally complied with reducing grid losses, can affect other network indicators such as voltage profile and power quality (PQ) indices. One of the most common PQ problems that must be dealt with, is harmonic distortions. Harmonic distortions can have district effects on distribution grids like causing inaccurate operation of control systems and measuring devices. The abovementioned problems can lead to an aggregative harmonic resonance condition in the grid which if not attended, may lead to a capacitor bank explosion [1]sensitive nonlinear loads such as load commutated inverter drives are increasingly being used by industrial consumers. In one hand, sensitive nonlinear loads can induce parallel resonance condition to the network and in the other hand their continuous operation may be interrupted due to voltage sags. Therefore, power quality parameters associated with the secure performance of sensitive nonlinear loads must be monitored to avoid the adverse effects of parallel resonances and financial losses due to voltage sags. In this paper, a new approach based on the area of vulnerability to voltage sags and harmonic resonance mode analysis is proposed to determine the optimal number and the best location of power quality monitors (PQMs.

Nowadays, the use of non-linear loads such as inverters and variable speed drives is growing in industries. The use of these loads, despite the advantages like low initial construction cost and more controllability and efficiency, is the cause of disadvantages such as harmonic production. As a result, to prevent large financial losses in industrial sectors, it is required to improve the performance of these loads while facing harmonic distortions [2], [3].

As stated, many different types of research have been executed in the field of harmonic reduction methods, one of the most common is the implementation of harmonic filters. In [4]tuned frequency, voltage unbalance factor, voltage magnitudes and harmonic distortion based on power quality standard limits. The optimization problem is solved using genetic algorithm in which the filters locations, their connection types and parameters for each phase of the system are determined. Simulations are carried out using

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three-phase unbalanced 33-bus and 69-bus distribution test feeders to demonstrate the viability and efficiency of the proposed formulation to obtain results with total harmonic distortion lower than 5%, voltage unbalance factor lower than 1%, power factor greater than 0.92 and voltage magnitudes between acceptable limits. The main contributions of this paper are the formulation considering multiple power quality indexes in three-phase unbalanced distribution systems, the possibility of the filters to be connected in Y or Δ to satisfy the objective function and the constraints of the optimization problem. Additionally, security constraints related to the operation of the capacitor banks of the filters are considered in [4] passive harmonic filter programming is presented as an optimization problem with the objective function of voltage sag reduction while considering constraints such as voltage limits, regulation frequency, voltage balance factor, optimized power factor, and harmonic distortion limits. [5] considers daily load change as well as distribution system rearrangement in the programming of single-tuned passive harmonic filters. Genetic algorithm (GA) had been assigned to determine the location and size of programming passive filters as well as grid rearrangement. In [6]but their allocation in the system requires attention. Depending on the filters location, harmonic distortion could increase at other nodes. The methodology of this study is based on harmonic flow simulation in the Alternative Transient Program (ATP/EMTP, using the genetic optimization algorithm, the placement of single-phase harmonic filters in the distribution grid has been aligned with the objective of reduction in harmonic distortion and initial investment cost of these filters. In [7], considering the uncertainty of the distribution system and using the grasshopper optimization algorithm, the design of passive harmonic filters has been carried out with the aim of harmonic distortion reduction. [8] assigns genetic optimization algorithm and Monte-Carlo simulation method to fulfill the probabilistic nature of single-tuned passive harmonic filter programming while being in the presence of PV systems. The optimization problem aims to decrease the cost of passive filter installation, energy losses, and harmonic distortion. [3] introduces a novel approach to designing passive harmonic filters considering voltage sags to reduce harmonic distortions and damages caused by them. [9] tries to explain the designing of passive harmonic filters using a multi-objective Prato-based Bay algorithm (Pb-Moba) to improve the harmonic constrained hosting capacity (HC-HC) of distributed generation (DG) renewable systems with harmonic pollution. Also, in another study [10], unlike the conventional problems of planning passive harmonic filters, the problem of selecting three high-pass harmonic filters (i.e., HP 2 filter, HP 3 filter, and C-type filter) is solved based on an analytical method. In [11], the fourth-order passive filter has been presented. Moreover, this paper categorizes the mathematical design of these types of filters using the crow spiral search algorithm (CSSK) with the aim of total demand distortion (TDD) reduction.

1- 2- Motivations and Contributions

Considering the abovementioned articles as one of the most important works on the topic and examining the rest of the available methods, it is obvious that there are drawbacks to the use of existing designing passive harmonic filter methods as follows: (i) Previous methods have neglected the effects of daily load changes and different network configurations on the duty limits of the passive harmonic filters such as maximum peak voltage capacitors, and maximum RMS current passing through the capacitor, which may result in serving capacitor overload; and as a result, the lifespan of capacitors decreases. (ii) Prior methods have not determined the most severe harmonic conditions in the network. This concern is crucial because the number and location of passive harmonic filters can be affected by system conditions. In other words, if filter planning is not performed concerning the most severe harmonic conditions in the network, the provision of power quality constraint is not guaranteed. (iii) It can be seen that none of these works provide passive harmonic filters probabilistic optimal planning on distribution systems while taking into consideration the effect of temperature change on filter parameters. As a matter of fact, passive harmonic filter parameters might alter due to temperature change which may cause a malfunction in filters.

This paper presents a probabilistic method for optimal planning of passive harmonic filters taking into account daily load changes and possible arrangement of the distribution grids simultaneously as well as considering requirements for the passive filter capacitors rating (i.e., duty limits). Also, the impact of temperature change in harmonic filter parameters is considered in planning the passive harmonic filter process. Furthermore, this method finds a solution where the proposed filters work well in all possible network configurations and do not cross any of the network constraints. To do so, first using the normal distribution function and Monte-Carlo method, the probabilistic behavior of the modeled non-linear load and the distribution arrangement of the distribution grid are determined. Next, the worst case of the network in terms of harmonics is calculated using the system average total harmonic distortion index (SATHD). Then, the programming of passive harmonic filters is executed according to the daily load profile and different network configurations. At this stage, a two-level probabilistic optimization problem based on the genetic algorithm (GA) and Monte-Carlo simulation method (MCS) is at hand, in which, modeling the behavior of the distribution network operator is performed through grid rearrangement with the aim of minimizing losses (as a lower case problem) at predetermined hours of the day, and then programming of the passive harmonic filter (as a higher case problem) is performed according to the daily load profile and different network configurations. In the next step, the final solutions of the optimization problem are calculated using the cumulative distribution function (histogram). Also, at this stage, an optimal solution is presented for the most extreme case of the network. In the end, the effect of temperature and filter design requirements are also examined. It should be noted that during this process, all types of passive harmonic filters are considered.

2- Probabilistic Optimal Planning of Passive Harmonic Filters

2- 1- Passive Harmonic Filter

A passive harmonic filter is a cost-efficient method and one of the most common approaches that can reduce harmonic distortion and protect non-linear loads from interruption, interference, and breakdown [12]. In this paper, single-tune passive harmonic filters, second-order high-pass filters, third-order high-pass filters, and C-type filters have been utilized to reach the mentioned goal. Single-tune filters consist of a capacitor in series with a reactor. The reactance value of the capacitor and reactor is set in such a manner that the impedance of the branch becomes zero in a certain harmonic frequency. Moreover, the capacitor provides the required reactive power in compensation. The second-order filter consists of a capacitor in series with a parallel set of reactors and resistors. The size of the filter elements is selected in such a way that the filter performance at frequencies lower than the tuning frequency is similar to a single-tuning filter, and at frequencies above the tuning frequency, it operates similarly to the first-order filters. Third-order filters have a high capacitive reactance at the main frequency and frequencies lower than that, and the impedance mostly shows resistance in higher frequency bands. The parallel inductive reactance branch has a small impedance at low frequencies, which causes the RC branch to become short-circuit and therefore removed from the circuit. This causes the third-order filter to operate similarly to the single-tuned filter at frequencies below the tuning frequency. At high frequencies, the inductive reactance branch operates as an open circuit, which makes the current pass through the capacitors and the resistances in series with them. Thus, the third-order filter acts like a first-order filter at frequencies above the tuning frequency. Due to the presence of capacitor type C2, the losses of the third-order filters are lower than those of the second-order. Also, the notch depth in the third-order filter is greater than that of the second-order one. The performance of the C-type filter is between the performance of the second and third-order filters. The parallel LC branch is set with a resistor at the main frequency and therefore, at the main frequency, the resistance branch is shorted and the loss at the main frequency reaches zero. In doing so, all the reactive power required at the main frequency is provided by the capacitor C1. The value of the reactor is adjusted so that it creates series resonance with the sum of the capacitors C1 and C2 at the frequency of the desired setting, and as a result, the C filter will have the same performance as the single-tune filter. At higher frequencies, the value of inductive reactance increases and as a result, the filter has the same performance as the first-order filter. The mentioned passive harmonic filter impedance value is calculated according to (1) to (4) [12].

$$Z_{ST} = R + j\left(hX_L - \frac{X_C}{h}\right) \tag{1}$$

$$Z_{2^{th}-order} = \frac{R(hX_L)^2}{R^2 + (hX_L)^2} + j\left[\frac{R^2 hX_L}{R^2 + (hX_L)^2} - \frac{X_C}{h}\right] \tag{2}$$

$$Z_{3^{th}-order} = \frac{R\,(hX_L)^2}{R^2 + (hX_L - \frac{X_C}{h})^2} + j\left[\frac{R^2 hX_L - hX_L^2 X_C + \frac{X_L X_C^2}{h}}{R^2 + (hX_L - \frac{X_C}{h})^2} - \frac{X_C}{h}\right] \tag{3}$$

$$Z_{C-type} = \frac{R\,(hX_L - \frac{X_L}{h})^2}{R^2 + (hX_L - \frac{X_L}{h})^2} + j\left[\frac{R^2 (hX_L - \frac{X_L}{h})}{R^2 + (hX_L - \frac{X_L}{h})^2} - \frac{X_C}{h}\right] \tag{4}$$

In all the mentioned types of filters, the main capacitor is usually selected to compensate for the voltage and improve the power factor. In the equations above R, X_L, X_C, and h_n are resistance, inductor reactance, capacitive reactance, and harmonic order respectively. Also, h_n and the relationship between X_L and X_C are obtained from (5) and (6), respectively [12].

$$h_n = \frac{f_n}{f_1} = \frac{1}{\omega_1 \sqrt{LC}} \tag{5}$$

$$X_L = \frac{X_C}{h_n^2} \tag{6}$$

For third-order and C-type harmonic filters, the damping constant ratio, harmonic order, and X_C are calculated using (7)-(9) [12].

$$m = \frac{L}{R^2 C_2} \tag{7}$$

$$h_n = \frac{1}{2\pi f_1 R C_2} \tag{8}$$

$$X_C = \frac{1}{\omega C_2} \tag{9}$$

Also, for the third-order HP harmonic filter, C_1 is equal to C_2. In addition, for C-type HP harmonic filter, C_1 is calculated using (10) [12].

$$C_1 = \frac{1}{\omega_1^2 L} \tag{10}$$

Moreover, the quality factors of ST and second-order HP harmonic filter are calculated as (11) and (12), respectively [12].

$$Q_{ST} = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{11}$$

$$Q_{2^{th}-order} = R\sqrt{\frac{C}{L}} \tag{12}$$

2- 2- Passive Harmonic Filter Design Requirements

Harmonic distortions may lead to serve capacitor overload, resulting in a decrease in capacitors. Therefore, there are requirements for the passive filter capacitors rating such as maximum voltage as well as RMS values of voltage and current of the capacitor, which is called duty limit and should be considered in the design of passive filters. The duty limit and its permissible limits according to peak voltage, RMS voltage, RMS current, and reactive power restrictions, are presented in (13) to (16) respectively [13].

$$\sum_{h=1}^{h=h_{\max}} V_h \leq \ 1.2\, V_1 \tag{13}$$

$$\sqrt{1+THD_v^2} \leq \ 1.1 \tag{14}$$

$$\sqrt{1+THD_i^2} \leq \ 1.3 \tag{15}$$

$$\sum_{h=1}^{h=h_{\max}} V_h\, I_h \leq \ 1.35 \tag{16}$$

In (13)-(16), V_h, V_1 and I_h are the voltage magnitude at the h^{th} harmonic, magnitude of the voltage at fundamental frequency, and magnitude of the current at the h^{th} harmonic, respectively. Besides, THD_v and THD_i are total harmonic distortion values of voltage and current, respectively.

2- 3- Uncertainty of Passive Harmonic Filter Parameters

Practically, passive harmonic filter parameters can change due to factors such as aging as well as temperature changes. For example, the capacity of capacitors usually decreases between 0.4% and 0.8% for every 10-degree increase in temperature [14]. Also, due to aging, the adjustment frequency of passive filters (h) may vary over the years. Therefore, to prevent the aging adverse effects, the adjustment frequency of passive filters is calculated from (17) [15].

$$h = h_n + (\delta h_n) \tag{17}$$

Where δ is calculated from the following equation [15].

$$\delta = \frac{\Delta f}{f} + \frac{1}{2}\left(\frac{\Delta L}{L} + \frac{\Delta C}{C}\right) \tag{18}$$

In (18), δ, Δf, ΔL and ΔC are the adjustment coefficient, frequency deviation, inductance changes, and capacitance changes, respectively.

2- 4- SATHD Index

Harmonic distortions can have destructive effects on the power grid. Generators and motors are greatly affected by the presence of harmonics in the networks to which they are connected. Harmonics cause losses in capacitors and motors, and the lifespan of capacitors shortens as the harmonic increases. Power cables are inherently capacitive and their capacitance can lead to resonance with inductive parts of the network. Resonance and self-harmonic risks can cause cables to be subjected to overvoltage or corona. In power electronic equipment, if there is a significant level of harmonic distortion, the performance of this equipment may suffer a great malfunction. Harmonic currents increase heat and losses in switchboards. Similarly, voltage distortion can cause problems for voltage transformers and relays connected to them. Moreover, current distortion can increase losses in transformers. Harmonics can cause the relay to malfunction. Also, harmonics can disrupt the speed of operation of electromagnetic differential relays. Fuses can malfunction under the influence of harmonics. Also, in a system, continuous burning of fuses for no reason is a sign of the presence of unexpected harmonics or changes in the combination of harmonics in that system. Therefore, in this paper, the SATHD index is used to determine the most severe harmonic conditions in the network. This indicator is critical for system operators, especially when planning passive filters. SATHD is calculated from the following equation [16].

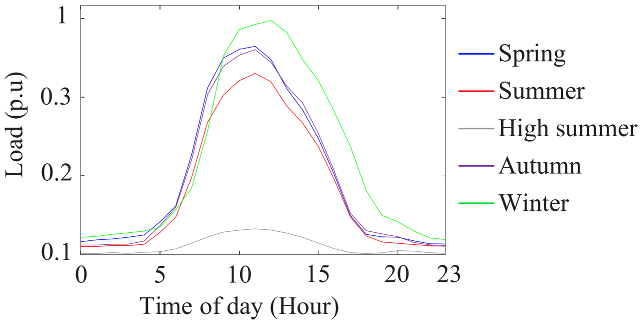

Fig. 1. Electric load profile for educational consumers in different seasons of the year

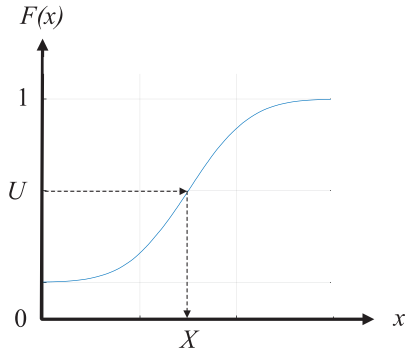

Fig. 2. The reverse conversion method

$$SATHD = \frac{\sum_{j=1}^{N} L_j \times THD_j}{L_T} \tag{19}$$

Where N and THD_j are the number of buses and THD at bus j, respectively. In addition, L_T and L_j are the total connected kVA of the loads served from the system and bus j, respectively.

2- 5- Uncertainty of Electric Loads

Electrical load characteristics will vary depending on the type of customer (i.e., residential, commercial, and industrial), environment temperature, and days of the week, weekends, and seasons. Power generators use this information to plan the amount of required power at any given time. Usually, the electrical load profiles in the distribution network change, which can affect the number of harmonics injected into the network as well as the network voltage profile. An example of an electric load profile for educational (schools, universities, etc.) consumers in different seasons of the year has been presented in Fig. 1.

Also, the behavior of electric loads can change probabilistically. The amount of demand for this type of load depends on several factors, some of which are fixed and have a specific trend, and some others are a function of other factors or are almost random. As an example, in the household consumption section, the most important factors affecting the amount of load can be expressed as the number of household consumers and the social and geographical conditions in the targeted area. To solve a problem in a probabilistic manner, various methods such as statistical methods are employed. Monte Carlo simulation is a statistical method to solve a probabilistic problem, which uses several techniques to generate random variables. In this article, based on equations (20) and (21), the inverse transformation method is used due to the high convergence speed and reduction of the computational burden [17].

$$F^{-1}(y) = \inf\{x : F(x) \geq y\} \text{ , } 0 \leq y \leq 1 \tag{20}$$

$$X = F^{-1}(U) \tag{21}$$

Where X is a random variable with a cumulative distribution function and U is a number between 0 and 1. Fig. 2 demonstrates the reverse conversion method, whose steps are as follows:

1. Generate U from $U(0,1)$
2. $X \leftarrow F^{-1}(U)$
3. Return X

According to the central limit theory, the average distribution of network loads can be modeled by a normal distribution function, even if the distribution function of some loads is not normal [8]. In this paper, non-linear load behavior is considered with a normal distribution function. Therefore, it can be concluded that the harmonics produced by these loads can also be modeled by a normal distribution function.

2- 6- Possible Configuration of Distribution Systems

Usually, the rearrangement of the distribution network is processed with goals such as reducing network losses which can affect many other network indicators such as voltage profile and power quality. In this paper, the method presented in [5] is used to rearrange the distribution network. firstly this method, rearranges the network during a 24-hour time period, according to the method presented in [18], to minimize the times of switches or breakers getting connected and disconnected (increasing the lifespan of switches or breakers), the 24-hours is divided into two-time intervals h_1 and h_2.

$$OF = \max\left\{ \left| a - b \right| \right\} \tag{22}$$

In this equation, a and b are the average load values in the

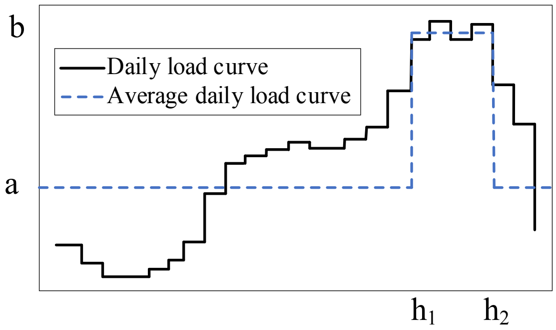

Fig. 3. The normal distribution function for random variable x

first and second time period, respectively. According to Fig. 3, the 24-hour is divided in such a way that equation (22) is maximized. Then, the rearrangement problem is formulated to reduce the energy loss of the entire network in the presence of non-linear loads in a certain period of time as 23 [5].

$$OF_{R_s} = \sum_t P_{Loos_{t,s}} = 3 \times \sum_t \sum_j R_j \sum_h \left| I_{h,j,t,s} \right|^2 \tag{23}$$

In which *j*, *h* and *s* are the number of grid lines, harmonic orders, and the number of rearrangements per day, respectively. In addition, OF_{R_s} is the total energy loss of the network as an objective function of the rearrangement problem at iteration *s*. Moreover, $P_{Loos_{t,s}}$ and R_j are total grid losses at hour t per day and resistance at line *j*, respectively. Besides, $I_{h,j,t,s}$ is harmonic current at harmonic order *h* and hour *t* in line *j* and rearrangement *s*.

In the mentioned rearrangement problem, while maintaining the radial structure of the network and taking into consideration that every load is connected to the network, the following constraints must be satisfied [19].

$$V_{Min} \le V_i \le V_{Max} \tag{24}$$

$$Q_{C,total} \le Q_d \tag{25}$$

$$S_k \le S_k^{\max} \tag{26}$$

$$N_{branch} = N_{bus} - 1 \tag{27}$$

Where V_i is the voltage in the bus *i* and V_{min} and V_{max} are the minimum and maximum permissible voltages in the i^{th} bus, respectively. Also, $Q_{C,total}$, and Q_d are total compensated reactive power with the capacitor bank and total reactive power on the demand side, respectively. In addition, S_k is the apparent transmitted power in the k^{th} line and $S_k^{\max}$ is the maximum allowed apparent transmitted power. Besides, N_{branch} and N_{bus} represent the total number of branches and busses of the distribution system, respectively.

2- 7- Objective Function and Constraints

In this paper, a single-objective optimization problem is defined for the optimization of two objective functions, containing the reduction of power losses and the minimization of passive harmonic filter costs. The objective function of the passive harmonic filter planning problem is defined as the sum of costs caused by network losses and filter investment. The total cost function can be presented in the form of annual cost as (28) [20], [21].

$$OF_P = \left(C_{inv} + C_{loss}\right) = \frac{IR\left(1+IR\right)^N}{\left(1+IR\right)^N - 1}\left(C_{inv}^P + C_{co}^P\right) + C_{EL}^P \tag{28}$$

In equation (28), C_{inv} and C_{loss} present the loss cost and investment cost of passive harmonic filters, respectively. C_{inv}^P and C_{co}^P are the present value of passive harmonic filters investment cost and cost of capacity occupation, respectively. C_{EL}^P is the annual energy loss cost, *IR* is the economic interest rate, and *N* is the years selected in the planning horizon based on the lifetime of the passive filter.

C_{inv}^P is calculated as the following equation [22].

$$\begin{aligned} C_{inv}^P &= \sum_i \sum_m \left(K_C\, Q_{Ci,m}^n + K_L\, Q_{Li,m}^n\right) \\ &= \sum_i \sum_m \Bigg(K_C\, Q_{C_i,m}^n + K_L \frac{Q_{C_i,m}^N}{\left(V_{C_i,m}^n\right)^2} \sum_h \frac{m^2 h^3 \left(V_i^h\right)^2}{\left(h^2 - m^2\right)^2}\Bigg) \end{aligned} \tag{29}$$

In the presented equation, *i* is the bus number index and *m* is the predefined filter tuning order index. Also, K_C and K_L are the unit cost of the selected capacitor and inductor for each harmonic filter, respectively. Besides, $Q^{n}_{Ci,m}$ and $Q^{n}_{Li,m}$ presents the nominal reactive power of the capacitor and the sum of the reactive power of the inductor in all harmonic frequencies of the m^{th} order filter in the i^{th} bus. In addition, the total energy loss cost of the system in the presence of non-linear loads can be formulated in the form of equation (30) [5].

$$C^{P}_{EL} = 3 \times K_{CEL} \times \sum_{s}\sum_{t}\sum_{b} R_b \sum_{h} \left| I_{h,b,t} \right|^2 \tag{30}$$

Where K_{CEL} is the energy loss cost unit. Similarly, the capacity occupation cost can be calculated using (31) [5].

$$C^{P}_{CO} = K_{CCO} P_{LOSS,Max} \tag{31}$$

In equation (31), $P_{LOSS,Max}$, and K_{CCO} are the maximum power loss and the cost of capacity occupation cost, respectively.

In this article, the constraints (32) to (35) have been aligned for the programming problem of the passive harmonic filter [12], [23]..

$$THD_{i,h} < THD_{Max} \tag{32}$$

$$IHD_{i,h} < IHD_{Max} \tag{33}$$

$$V_{Min} \leq V_{i,t} \leq V_{Max} \tag{34}$$

$$PF_{\min} \leq PF \leq PF_{\max} \tag{35}$$

Where *IHD* and PF are calculated from the following equations [24].

$$IHD_{i,h} = \left(\frac{V_{i,h}}{V_{i,1}} \right) \times 100 \tag{36}$$

$$PF_i = \frac{P_i}{S_i} = \frac{\sum_{h=1}^{h_{\max}} \left| V_{i.h} \right| \left| I_{i,h} \right| \cos\theta_h}{\sum_{h=1}^{h_{\max}} V^2_{i,h} \sum_{h=1}^{h_{\max}} I^2_{i.h}} \tag{37}$$

2- 8- Presented Method for the Probabilistic Design of Passive Filters Considering the Possible Configurations of the Network

In the current article, a probabilistic method for the design of passive harmonic filters is presented taking into account all the possible configurations of the network. Two separate genetic algorithms (GA) cores are implemented to solve the main problem of passive harmonic filter programming and reconfiguration. To do so, first, the load profile has been taken into account, and using the method mentioned in subsection 2.6, the 24-hour time period has been divided into two time intervals h_1 and h_2. Then, the maximum iteration for GA and the number of samples produced for MCS are specified. In the next step, after defining the PDF function for non-linear loads, the inverse CDF is calculated. As explained in subsection 2.5, the inverse transformation method was utilized to generate random variables (active and reactive power of non-linear loads) to increase the convergence speed of MCS. To generate a random sample which is assigned as the active and reactive power of non-linear loads, a random number is generated for each non-linear load according to the allocated normal distribution function with nominal power of the same load as the mean amount and a standard deviation of 20%. Next, according to the objective function (23), distribution network rearrangement (low-level problem) is accomplished using the method presented in subsection 2.6, for the first time interval, in other words, in the proposed model, the lower-level optimization specifies the network topology in different time periods during the planning horizon of planning of the passive harmonic filter. Then, according to the objective function (28) passive harmonic filter planning (high-level problem) is performed, and taking into consideration different topologies of the network, the size, and location, as well as frequency of passive filter adjustment, are determined. It is clear that for N_f number of filters that are optimally located adding additional filters increases the cost of the filter design. Because of not having a previous assumption about the optimal value of N_f, the process first starts with $N_f = 1$. Next, the selected passive harmonic filters are added to the network and the harmonic load flow is performed while considering the harmonics of the non-linear loads. Then, the energy loss, voltage THD, and cost function are evaluated and the best solution is saved in each Monte-Carlo iteration and the same method is repeated for the second time interval. In the next step, the stopping criterion for creating the scenario is checked by MCS, and finally, because there is an optimal solution in each time interval as many times as the Monte-Carlo simulation is repeated, to choose a solution that is acceptable in almost all different levels of network load, the histogram graph of the obtained solutions is drawn and the solution that has the most repetition is selected and printed as the best answer for the problem. Fig. 4 indicates the flowchart of the comprehensive solution of probabilistic planning and rearrangement of the passive harmonic filter. In the proposed flowchart, N_{MCS}, t , and *iter* are the number of samples generated for MCS, time period, and the number of iterations of GA, respectively.

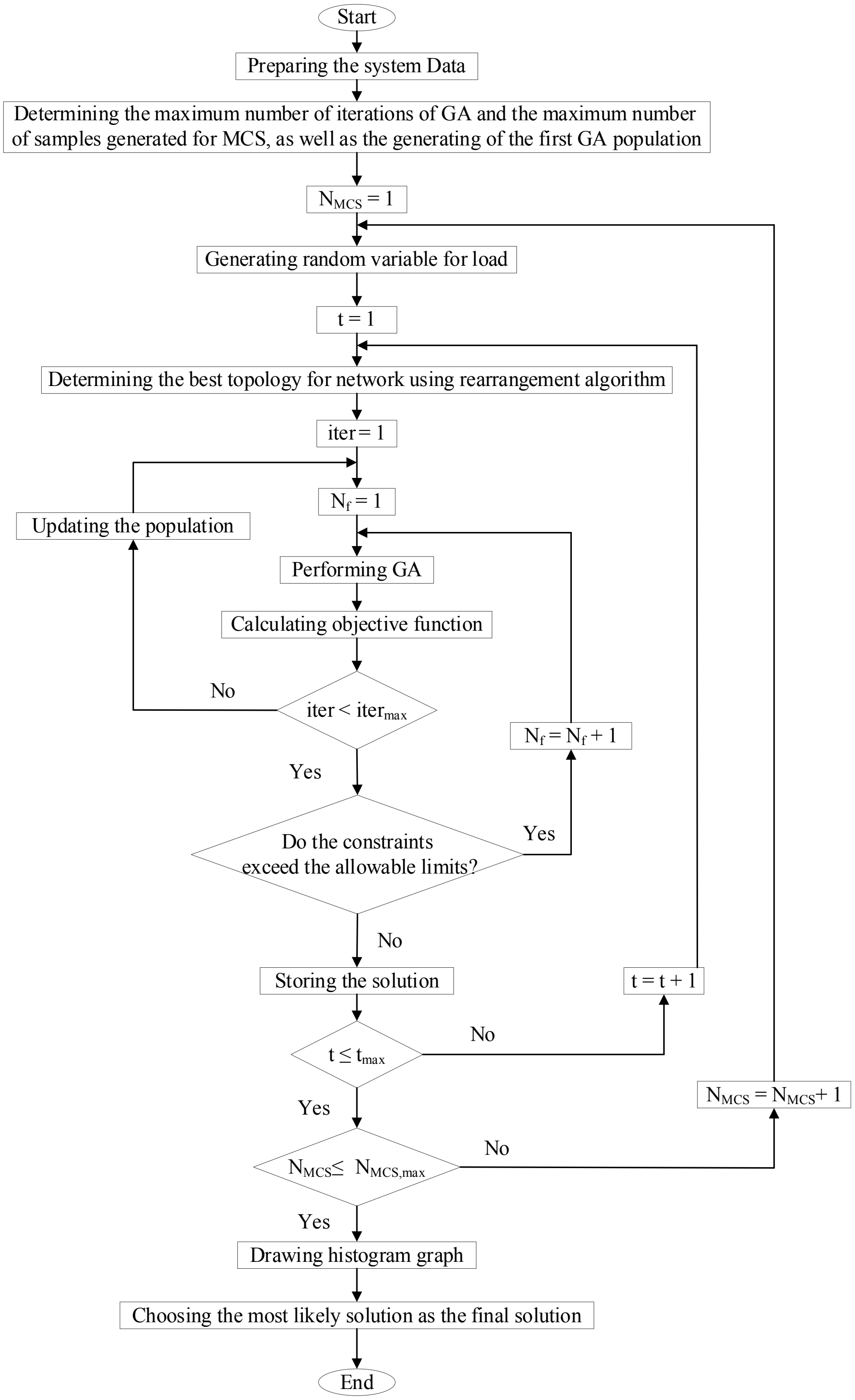

Fig. 4. Flowchart of the comprehensive solution of probabilistic planning and rearrangement of the passive harmonic filter

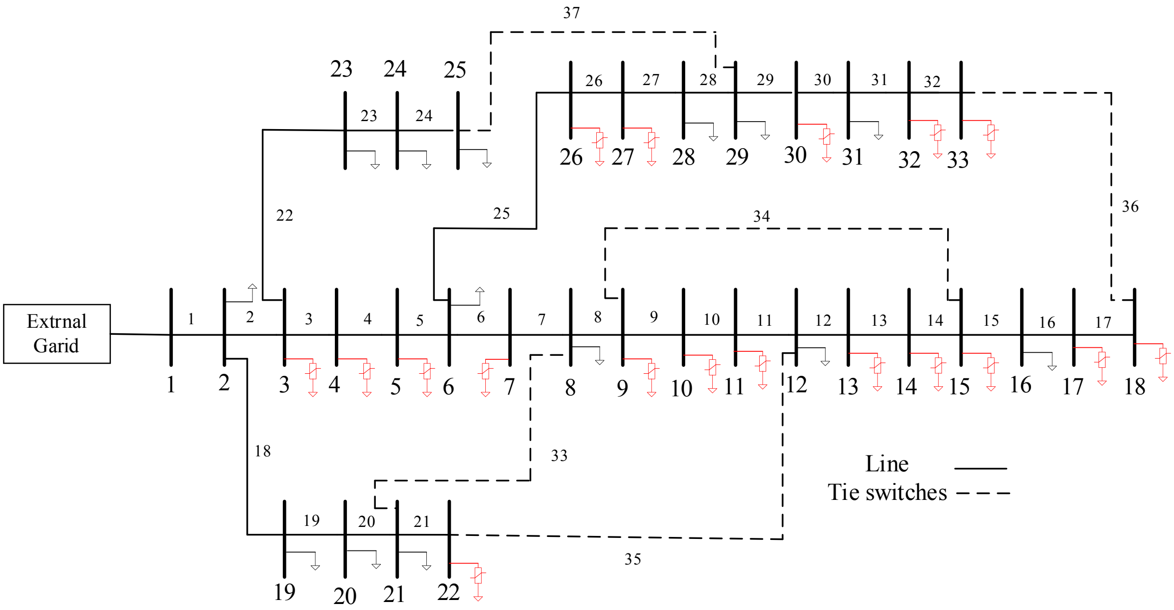

Fig. 5. The single-line diagram of the studied network

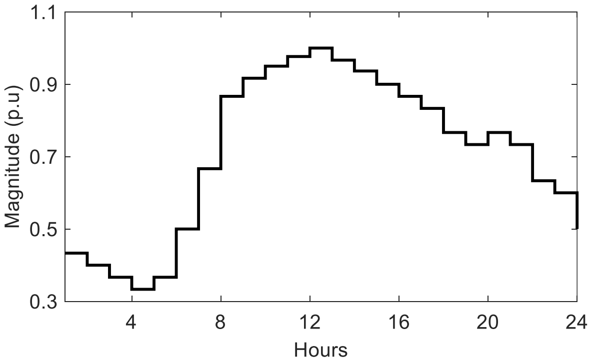

Fig. 6. The load profile of variable loads

3- Simulation Results

3- 1- Test System

In this article, in order to evaluate the proposed method, the modified IEEE 33-bus network presented in [5] has been utilized, in which the power of linear loads has reduced to 30% of nominal values, and 18 variable non-linear loads have been added to the network. Fig. 5 shows the single-line diagram of the studied network. Fig. 6 presents the load profile of variable loads.

Information on non-linear loads in the studied network is given in Table 1. In this table, type 1, 2, and 3 loads are distinguished as adjustable speed drive, six-pulse variable frequency drive, and six-pulse converter, respectively. Also, the harmonic current spectrum of the non-linear loads assigned in this network is indicated in Table 2. Besides, the used parameter values related to the presented method, are given in Table 3. In addition, the fixed values of the proposed algorithm parameters (i.e., two GA-cores) are shown in Table 4. It should be noted that the permitted iteration of Monte-Carlo samples is considered 2000.

Table 1. The amount of power of the non-linear loads added to the 33-bus network

Bus	Load type	P (kW)	Q (kVAr)
3	1	100	40
5	2	200	150
6	3	100	80
7	1	200	150
9	2	100	80
10	2	200	150
11	3	500	400
13	2	350	270
14	2	650	450
15	2	250	170
17	3	220	140
18	1	100	70
22	2	50	20
26	2	250	150
27	2	400	300
30	2	450	300
32	2	650	300
33	2	100	50

Table 2. Harmonic spectrum of nonlinear loads

Non-linear load type	Harmonic order	Magnitude (%)	Phase (°)
Adjustable speed drive (PWM)	1	100	0
	5	2	0
	7	1.2	0
	11	5.5	0
	13	3.7	0
	17	0.2	0
	19	0	0
	23	0.2	0
	25	0.4	0
	29	0	0
	31	0	0
Six-pulse variable frequency drive	1	100	0
	5	23.95	111
	7	6.08	109
	11	4.57	-158
	13	4.2	-178
	17	1.8	-94
	19	1.37	-92
	23	0.75	-70
	25	0.56	-70
	29	0.49	-20
	31	0.54	7
Six-pulse converter	1	100	0
	5	20	0
	7	14.3	0
	11	9.1	0
	13	7.7	0
	17	5.9	0
	19	5.3	0
	23	4.3	0
	25	4	0
	29	3.4	0
	31	2.2	0

Table 3. Values of parameters used in the paper

Parameter	Symbol	Value
Unit costs of the capacitor ($/kVAr)	K_C	6.42
Unit costs of the inductor ($/kVAr)	K_L	15.4
Interest rate (%)	IR	5
Filter lifetime (year)	N	15
The unit cost of energy loss ($/KWh)	K_{CEL}	0.05
The unit cost of capacity occupation ($/MW)	K_{CCO}	120000
Maximum filter number	$N_{fil,Max}$	18
Maximum total harmonic distortion (%)	THD_{Max}	5
Maximum individual harmonic distortion (%)	IHD_{Max}	3
Maximum bus voltage magnitude (p.u)	V_{Max}	1.1
Minimum bus voltage magnitude (p.u.)	V_{Min}	0.9
Maximum bus power factor	PF_{Max}	1
Minimum bus power factor	PF_{Min}	0.9
Frequency variation (%)	Δf	2
Inductance variation (%)	ΔL	-10 ~ 20
Capacitance variation (%)	ΔC	-4.5 ~ 6.5

Table 4. Values of Set the parameters for two GA-cores

Parameter	Value	
	Reconfiguration	Filter planning
Population size	50	10
Crossover probability (%)	80	80
Mutation probability (%)	2	2
Maximum iteration	50	100

3- 2- Probabilistic Design of Passive Harmonic Filters

In this section, to show the effectiveness of the presented method, this method is applied in two different cases, i.e., the most probable case and the worst case, on the IEEE 33-bus network. Also, the results of this method have been compared with the results of the optimization method presented in [5].

3- 2- 1- Case 1

In this case, first, the 24-hour time period is divided into two-time intervals: 0-8 and 8-24 according to the procedure designated in subsection 2.6. In the next step, the possible topologies of the distribution network are examined while considering the possible load changes in these two time periods, and the optimized design problem of passive harmonic filters has been solved with the presented method. A histogram diagram of the active and reactive power of variable loads in the entire time period has been presented in Fig. 7 and Fig. 8, respectively.

Then, the passive harmonic filter parameters are calculated using the histogram method. Using the described method and the method presented in [5], selected topologies in each time interval, minimum voltage, network losses, and maximum THD of buses before applying filters are computed and shown in Table 5. Table 6 contains the parameters of the proposed passive filters resulting from the use of these two methods. According to Table 6, the proposed method suggests fewer passive harmonic filters. Also, the network parameters and filter cost using these two methods are given in Table 7. As can be seen, the proposed method has reduced the cost of harmonic filters by nearly 19%. Also, the maximum THD is

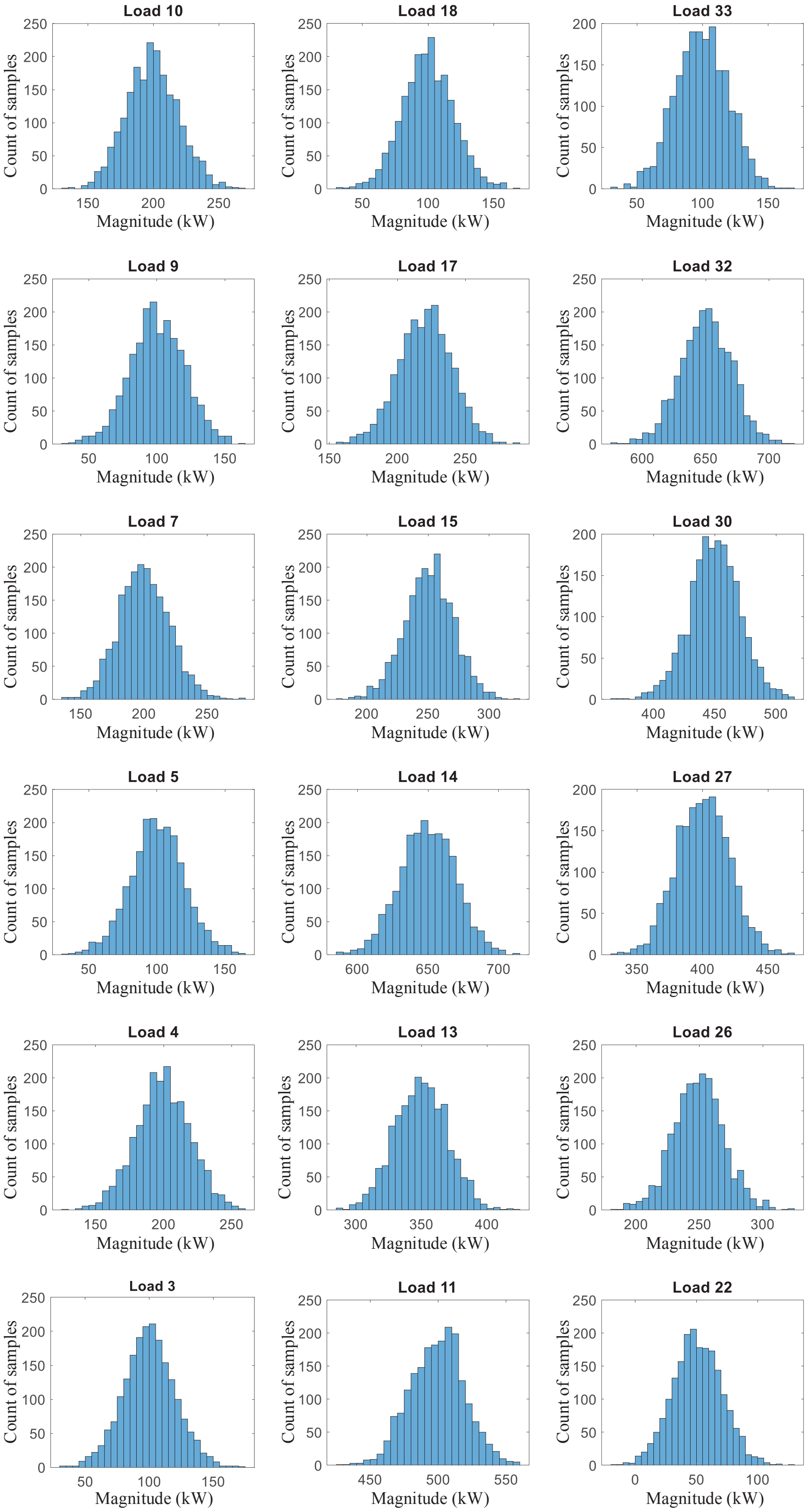

Fig. 7. Active power histogram diagram of variable loads in the entire time period

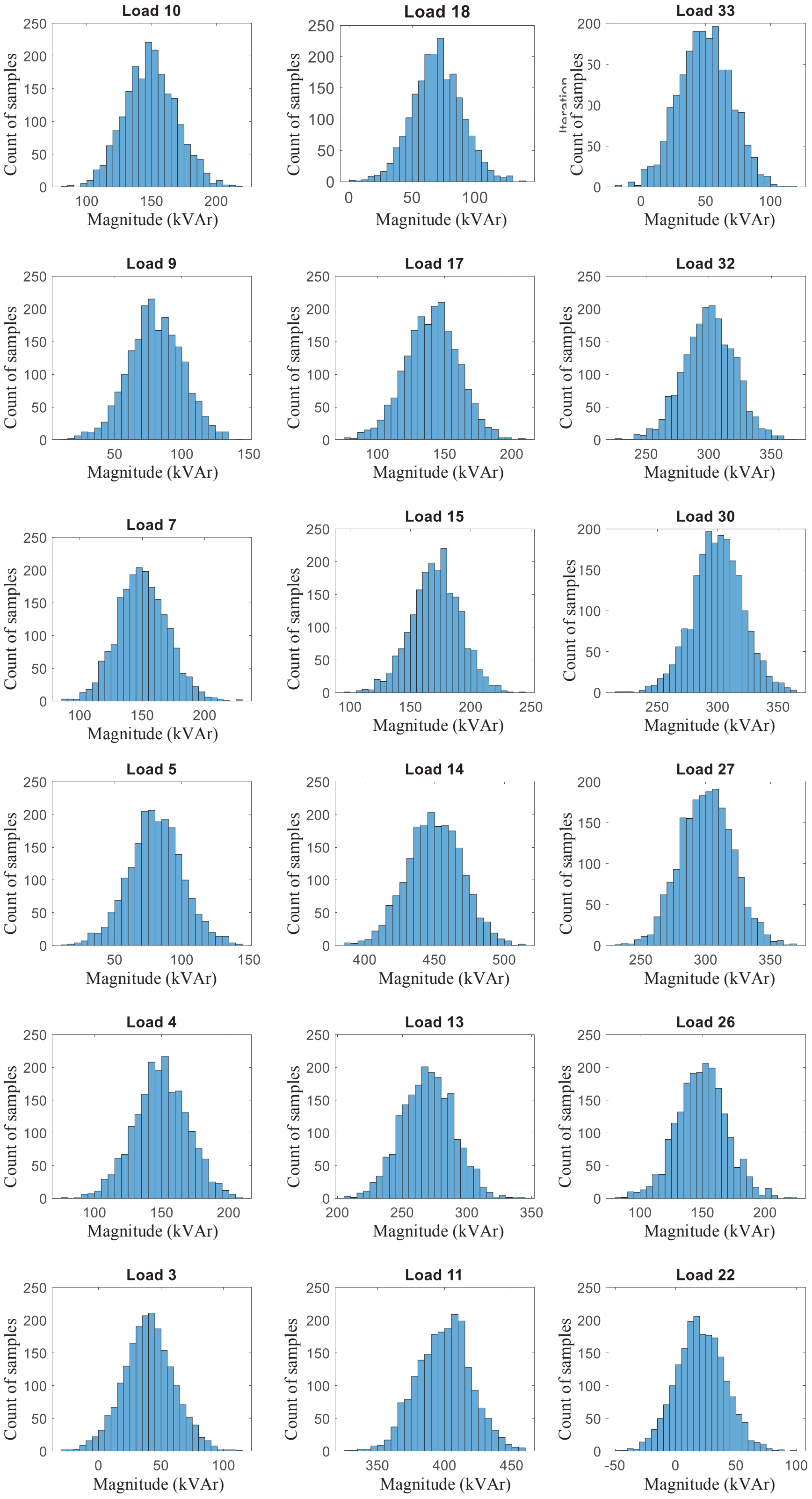

Fig. 8. Reactive power histogram diagram of variable loads in the entire time period

Table 5. Parameters of the network before filtering

Method	Hours	$\mathrm{THD}_{\mathrm{Max}}$ (%)	$\mathrm{V}_{\mathrm{Min}}$ (p.u)	Losses (kW)	Open-lines
Proposed method	0-8	5.44	0.93	106.67	5, 10, 14, 17, 27
	8-24	8.87	0.90	260.57	6, 10, 14, 28, 36
Proposed method in [5]	0-8	5.01	0.94	100.35	10, 14, 26, 32, 33
	8-24	9.04	0.90	238.49	7, 10, 14, 15, 28

Table 6. Parameters of passive filters using the proposed method

Method	Location	Type	R (Ω)	Q_c (kVAr)	Q_f	h
Proposed method	13	1	0.59	900	65	4.81
	15	1	0.89	600	65	4.81
Proposed method in [5]	7	1	3.96	150	60	4.7
	12	1	0.43	600	60	10.4
	13	1	0.74	800	60	4.7
	15	1	1.18	350	60	6.6

Table 7. Parameters of the network after filtering

Method	Hours	$\mathrm{THD}_{\mathrm{Max}}$ (%)	$\mathrm{V}_{\mathrm{min}}$ (p.u)	Losses (kW)	Filter cost ($)	Open-lines
Proposed method	0-8	2.28	0.96	88.98	10673.5	5, 10, 14, 17, 27
	8-24	3.35	0.92	188.81		6, 10, 14, 28, 36
Proposed method in [5]	0-8	3.4	0.96	97.45	13104.45	10, 14, 26, 32, 33
	8-24	7.75	0.93	188.29		7, 10, 14, 15, 28

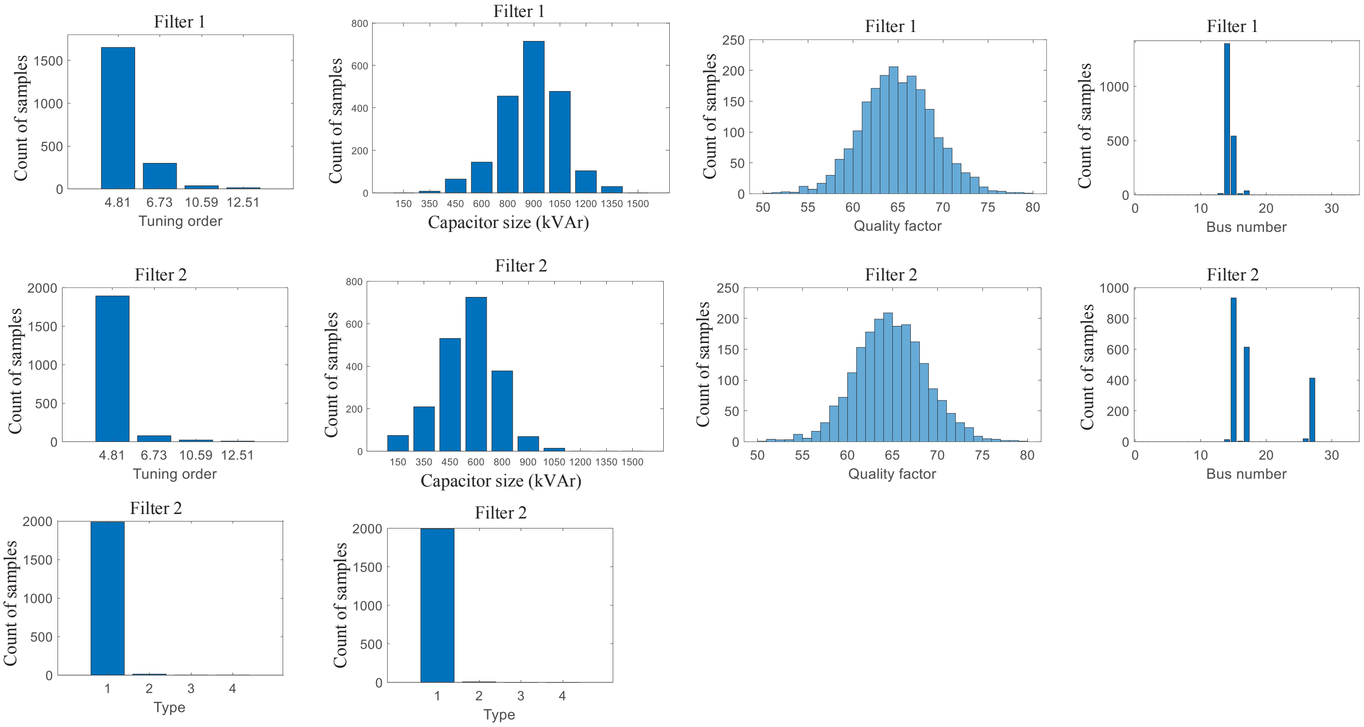

Fig. 9. Histogram diagram of the proposed filters parameters using the proposed method

Table 8. Parameters of the network before and after filtering

Case	SATHD	THD_{Max} (%)	V_{min} (p.u)	Losses (kW)	Filter cost ($)	Open-lines
Before filtering	132.04	16.77	0.81	722.71	-	6, 10, 14, 17, 28
After filtering	2.31	3.62	0.9	481	21346.7	6, 10, 14, 17, 28

out of the allowed range by applying the method presented in [5]. Besides, Fig. 9 shows the parameters of the proposed harmonic filters using the method provided by the histogram chart.

3- 2- 2- Case 2

The previous subsection aims to find a solution to the optimization problem of passive harmonic filter design in a manner that the proposed filters can work correctly in most possible cases. Since this solution is the most likely solution to the optimization problem, it may not be able to filter network harmonics in some cases. Therefore, according to the SATHD index presented in subsection 2.4, the worst network condition is determined harmonically. By using this index, it is possible to find a solution in which the proposed filters work well in all possible modes of the network and none of the limitations of the network are crossed. The values of the parameters of the network in the worst case in terms of harmonics before and after filtering are gathered in Table 8. Also, the values of the filters designed for this mode are presented in Table 9. In this case, four filters are installed in buses 11, 14, 17, and 18.

Also, the duty limits for the capacitors used in the filters designed by the proposed method have been checked and it has been found that none of these limits exceeded their allowable limits. The configuration of ST filters designed by the proposed method is shown in Fig. 10. In addition, the duty limits for the capacitors of these filters are shown in Table 10.

Table 9. Parameters of passive filters using the proposed method

Location	Type	R (Ω)	Q_c (kVAr)	Q_f	h
11	1	0.79	1050	41.61	4.81
14	1	0.79	1050	41.61	4.81
17	1	1.85	450	41.61	4.81
18	1	1.85	450	41.61	4.81

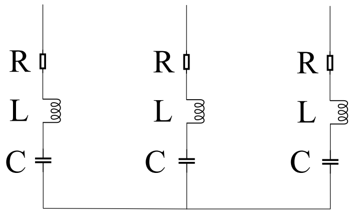

Fig. 10. Harmonic filters configurations

Table 10. Duty limits of capacitors for the proposed method

Duty	Bus 11	Bus 14	Bus 17	Bus 18	Limit (%)
Peak voltage	103.65	107.20	107.40	112.52	120
RMS voltage	100.03	100.17	100.18	100.62	110
RMS current	100.91	104.44	104.61	114.73	130
Reactive power	96.01	96.08	96.24	102.68	135

4- Conclusion

This paper presents a two-level method for probabilistic programming of passive harmonic filters considering possible network topologies. Due to the random nature of the electric loads, Monte-Carlo simulation was employed to model the probabilistic nature of the loads. To increase the convergence rate of MCS, the inverse transformation method was aligned to generate random variables. To increase the accuracy of the results of the proposed method, both the amplitude, as well as the phase angle of the harmonic currents, were considered in this research. Also, a new planning strategy of passive harmonic filters that cover different network topologies was introduced in the current article. Besides, the rearrangement problem based on loss reduction is presented as the lower-level optimization problem, and then the planning of passive filters as a higher-level optimization problem, is performed in certain daily time periods. Therefore, in this article, the optimal number of passive filters as well as their optimal location, adjustment frequency, quality factor, filter type, and its parameters are determined by solving an optimization problem. To do so, a genetic algorithm was applied to the optimization problem and then the best solution was obtained using the SATHD index. In order to demonstrate the effectiveness of the proposed filter design approach, a modified standard IEEE 30-bus network equipped with variable linear loads was studied in this research. The results of applying the proposed method declared that the designed filters can reduce THD and network losses while working properly in all possible network topologies.

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