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Enhancing power quality and loss optimization in distorted distribution networks utilizing capacitors and active power filters: A simultaneous approach

Hamed Rezapour [a,c], Farid Fathnia [b], Mohammad Fiuzy [a], Hamid Falaghi [c,*], António Mendes Lopes [d]

[a] Iran University of Science and Technology, Tehran, Iran
[b] Ferdowsi University of Mashhad, Mashhad, Iran
[c] University of Birjand, Birjand, Iran
[d] LAETA/INEGI, University of Porto, Porto, Portugal

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ABSTRACT

The importance of Power Quality (PQ) issues in modern power systems has been growing in the last years. Capacitors are employed for optimizing network losses and increasing the voltage profile. However, in harmonic polluted networks, the placement of capacitors at their economic optimal locations may not be feasible due to harmonic constraints. Under such conditions, harmonic filters can mitigate harmonic pollution and enable capacitors to be optimally placed. This paper presents a novel approach for simultaneously optimizing the allocation of Active Power Filters (APFs) and capacitors, to improve the harmonic condition, network losses, and voltage profile of distribution networks. The method models APFs as harmonic sources in the Harmonic Power Flow (HPF) procedure, while capacitors are modelled as their corresponding harmonic admittance. Furthermore, a modified Particle Swarm Optimization (PSO) algorithm is presented as the optimization tool. Three case studies were conducted on the IEEE 18-bus test system. In the first study, optimal capacitor placement was performed with no regard to harmonic constraints, reducing network losses by 326 kW. The harmonic limits were then considered and satisfied by optimal APF placement. The total cost resulted in $241,983. The second study considered harmonic limits in the procedure of optimal capacitor placement, improving voltage profiles and network losses, but exceeding some harmonic constraints, which were subsequently satisfied by APF placement. The solution yielded the total cost of $264,942. The third study introduced simultaneous allocation of capacitors and APFs, proving to be the most cost-effective strategy ($225,417 total cost), promising enhanced network performance and efficiency, and adding valuable insights for future power system optimization.

1. Introduction

Harmonic disturbances are the primary cause of Power Quality (PQ) degradation in modern power distribution networks, leading to the incorrect operation of protective devices, abnormal temperature rise, and additional losses [1]. Nonlinear loads containing power electronic switches are the primary sources of harmonic disturbances, but their use is becoming increasingly widespread. Furthermore, power and energy losses are other challenges in the efficient operation of power systems, which can be improved by the utilization of capacitors. This paper proposes an approach to simultaneous enhance power quality and optimize power and energy losses.

1.1. Motivation

Passive or Active Power Filters (APFs) are highly effective techniques for mitigating the impact of harmonics in distribution networks [2]. Passive filters reroute harmonic content of network currents away from system components through a bypass path. Conversely, active filters counteract the harmonic content of nonlinear load currents by injecting an equal but opposite-phase current, thus eliminating the harmonics [3].

Passive filters are inadequate in mitigating harmonic currents due to

* Corresponding author.
E-mail address: Falaghi@birjand.ac.ir (H. Falaghi).

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the complexities associated with time-varying harmonics and the extensive deployment of small power electronics-based apparatuses in distribution networks [3,4]. In contrast, APFs offer an effective solution for mitigating harmonic currents in distribution networks, primarily due to the adaptability provided by power electronic elements [5,6]. In general, APFs have several advantages over passive filters. APFs offer greater flexibility in compensating for a wide range of harmonic distortions and reactive power fluctuations. They have a faster dynamic response, allowing them to quickly detect and respond to changes in the system's harmonic content. APFs are load independent and can effectively compensate for harmonic distortions regardless of the connected load. They are compact in size and can be integrated into existing power systems without requiring significant space or modifications. However, APFs are generally more complex and expensive to implement compared to passive filters [5,6].

Optimal allocation of APFs has been the subject of numerous research studies. The primary optimization criterion of the problem typically revolves around minimizing the cost of APFs or a function closely tied to it, such as the size and the quantity of APFs. The constraints primarily pertain to maintaining the desired harmonic condition within the network, such as the voltage Total Harmonic Distortion (THD) and voltage Individual Harmonic Distortion (IHD). The primary goal of the optimal allocation of APFs is to improve the network's harmonic condition by utilizing APFs in the most economical manner.

On the other hand, shunt capacitors are widely used in distribution networks to enhance the voltage profile, correct power factor, and optimize system losses [7]. Capacitors can reduce harmonic pollution by acting as natural high-pass filters. However, harmonic disturbances can cause malfunction in shunt capacitors [8]. It is important to note that capacitors in a harmonic-polluted network can provoke harmonic resonance, resulting in large magnitudes of harmonic voltages and currents. Therefore, recent approaches have emphasized the consideration of harmonic interactions when applying capacitors in distorted distribution networks. The procedure of optimal allocation of capacitors that considers harmonic constraints may result in costly solutions compared to scenarios where no harmonic constraint is considered in the optimization process. Table 1, reported in [9], shows the results of an optimal capacitor placement problem tested on the IEEE 9-bus test system. Case 1 represents the network with no installed capacitor, Case 2 represents the capacitor-installed network without considering harmonic constraints, and Case 3 represents the capacitor-installed network with consideration of harmonic constraints. As shown, Case 3 results in costlier solutions than Case 2. In such situations, APFs can compensate harmonic currents and help capacitors be placed at their optimal economic locations.

It is worth noting that Table 1 also highlights the reduction of maximum THD in Case 2, where no harmonic constraint is considered in the optimization process. This reduction is attributed to the natural filtering behavior of capacitors. Leveraging this behavior in the optimal allocation of APFs can assist in harmonic compensation and decrease the size and cost of APFs. Therefore, the simultaneous allocation of capacitors and APFs can result in more economical solutions to achieve the desired network conditions regarding power quality and loss optimization.

In modern distribution networks, where harmonic reduction is commonly performed by utilizing APFs, capacitors can aid with their natural filtering behavior, rerouting harmonic currents to the ground rather than to system's components. In addition, APFs aid capacitors' placement on their economic optimal locations in a harmonic polluted network. The economic optimal locations of capacitors result from loss optimization approaches. Furthermore, compensating harmonic currents using APFs yields loss reduction.

Table 1
Results of an optimal capacitor placement problem tested on the IEEE 9-bus test system reported in [9].

Item	Case 1	Case 2	Case 3
Maximum THD (%)	24.85	7.0117	4.6096
Cost of system loss (US$)	581,368.9	507,127.0	508,233.4
Capacitor cost (US$)	0	33,900.0	54,900.0
Total Cost (US$)	581,368.9	541,027.0	563,133.4

In this paper, a novel optimization approach is presented to simultaneously allocate APFs and capacitors, which addresses existing issues and contributes to the advancement of power distribution network's optimization.

The following sections present a brief review of the problems related to optimal allocation of APFs and optimal capacitor placement in distorted distribution networks.

1.2. Literature review

1.2.1. Optimal allocation of APFs in distribution networks

Numerous researchers have extensively investigated the utilization of APFs in distribution networks. Grady et al. [10] devised an APF that minimizes voltage harmonics at all network buses, simultaneously optimizing the injection current based on various optimization criteria, like voltage waveform irregularities, telecommunication signal disruption, and motor load losses [11]. Chang et al. [12] concentrated on optimizing the allocation (i.e., siting and sizing) of a single APF, while their work in [13] was the pioneering attempt to explain the allocation of multiple APFs. Recent studies have focused on optimizing the application of APFs in distribution networks. Some papers [14–16] employed analytical methods, but due to their susceptibility to local optima, evolutionary algorithms, such as genetic algorithms (GA) and particle swarm optimization (PSO), have been employed to address the APF allocation problem [4,17–20]. An algorithm utilizing decision tree methodology for optimal APFs allocation was suggested in [21], and a brute force-based software was developed in [22] and tested on a low voltage network. To tackle uncertainty in the APF allocation problem, Zhao et al. [2] utilized a chance-constrained algorithm. Shivaie et al. [23] and Carpinelli et al. [24] demonstrated multi-objective approaches, while uncertainty was considered in multi-objective programming procedures [25]. Local control of APFs was addressed in [26], and a comprehensive review of APF allocation methods was presented in [27]. Table 2 summarizes the current approaches for optimal APF allocation in terms of the optimization method, optimization criterion, decision variables, and the number of APFs. Evolutionary algorithms like GA and PSO have been commonly employed in recent studies among the various optimization methods.

In fact, serious harmonic pollution and reduced power quality have resulted from the increasing usage of non-linear loads in power networks. One of the most effective approaches for correcting harmonic currents and augmenting power quality is the use of active filters. Capacitors have been shown to be highly important devices for enhancing the voltage profile and reducing power network losses. These kinds of equipment can be beneficial in reducing the network's range of harmonic voltages due to their natural filtering function. Of course, it should be noticed that the existence of capacitors under harmonic situations can produce resonance and cause extremely dangerous harmonic voltages and currents. It is feasible to locate this equipment concurrently by taking into consideration the overlapping behavior of active filters and capacitors regardless of harmonics and decreasing harmonic pollution in the network. Considering harmonic limitations in the capacitor placement, which is frequently carried out to decrease network losses and gain economic advantage, causes displacement of the best solution in the problem's answer space. This indicates that adding harmonic restrictions results in solutions with larger cost function values. In this case, the use of active filters aids in the process of correcting harmonic currents from capacitors and positioning them in accordance with their primary function (loss reduction). As a result, in the follow-up, an approach for simultaneous placement of these two

Table 2
Recent approaches in the field of allocation of APFs in distribution networks.

Reference	Optimization criterion (Min of)	Optimization method	Variables that have been optimized			Number of APFs	
			Location of APFs	Size of APFs	APFs Injection Current	Single	Multiple
[10]	harmonic voltages	NLP	✓	✓	✓	✓	–
[11]	squared of harmonic voltages	NLP	✓	✓	✓	✓	–
	squared of THDs						
	telephone interference factor						
	motor load losses						
[12]	injection current of APF	NLP	✓	✓	✓	✓	–
[14]	harmonic voltages	NLP & GRG2[1]	✓	✓	✓	–	✓
[4]	harmonic voltages	GA	✓	✓	✓	–	✓
	injection current of APFs						
[5]	power Losses, THD square of all buses & cost of APFs	GBDT[2]	✓	✓	✓	–	✓
[2]	cost of Active and Passive filters, Penalty for THD & IHD	GA	✓	✓	✓	–	✓
[15]	injection current of APFs	DE/MG	✓	✓	✓	–	✓
[23]	THD for all buses	MHSA[3]	✓	✓	✓	–	✓
	motor Load Losses						
	RMS current of APFs						
	harmonic Loss of transmission lines						
[17]	size of APFs	Fuzzy-MAPSO	✓	✓	✓	–	✓
[3]	THDs, MLLs, APLCs Current magnitude and HTLL	PSO	✓	✓	✓	–	✓
[19]	injection current of APFs	GA	✓	✓	✓	–	✓
	cost of APFs						
[18]	fixed and variable cost of APFs	Fuzzy-MABICA[4]	✓	✓	✓	–	✓
[25]	maximum value of SATHD (THD mean for all buses) in the study period	Trade-off/risk analysis	✓	✓	✓	–	✓
	cost of APFs and harmonic losses						
	maximum value of TDD arising in the study period						
[16]	harmonic voltages	GBDT	✓	✓	✓	–	✓
	RMS current of APFs						
Proposedmethod	cost of APFs	PSO	✓	✓	✓	–	✓

1. Generalized Reduced Gradient.
2. Generalized Benders Decomposition Theory.
3. Modified Harmony Search Algorithm.
4. Modified Adaptive Binary Imperialist Competitive Algorithm.

Table 3
Recent approaches in the field of allocation of capacitors in distorted distribution networks.

Reference	Optimization criterion (Min of)					Optimization method	HPF Method	Network Type	
	Voltage THD	Power Loss	Cost of Capacitors	Cost of Power Loss	Cost of Energy Loss			Balanced	Unbalanced (3 phase)
[34]	✓	_	_	_	_	GA	HP	_	✓
[35]	_	✓	_	_	_	GA	DHPF	✓	_
[36]	_	_	✓	✓	✓	Sine-Cosine	DHPF	✓	_
[37]	_	_	✓	✓	_	LV[1]	HP	✓	_
[38]	_	_	✓	✓	✓	ES[2]	HP	✓	_
[39]	_	_	✓	✓	_	GA[3]	HP	✓	_
[40]	_	_	✓	✓	✓	HM[4]	HP	_	✓
[41]	_	_	✓	✓	_	MSS[5]	HP	✓	_
[42]	_	_	✓	✓	✓	FDP[6]	HP	✓	_
[43]	_	_	✓	✓	✓	MSS	CHLF	✓	_
[44]	_	_	✓	✓	✓	GA	CHLF	✓	_
[45]	_	_	✓	✓	✓	Fuzzy	CHLF	✓	_
[46]	_	_	✓	✓	_	HM	HP	✓	_
[47]	_	_	✓	✓	_	MSS/LV	CHLF	✓	_
[48]	_	_	✓	✓	✓	Fuzzy/GA	CHLF	✓	_
[49]	_	_	✓	✓	✓	GA	HP	✓	_
[50]	_	_	✓	✓	✓	SA[8]/MSPSO[9]	HP	✓	_
Proposed Method	_	_	✓	✓	_	PSO	HP	✓	_

1. Local Variations
2. Exhaustive Search
3. Genetic Algorithm
4. Heuristic Method
5. Maximum Sensitivities Selection
6. Fuzzy Dynamic Programming
7. Particle Swarm Optimization
8. Sensitivity Analysis
9. Multi-Swarm Particle Swarm Optimization

types of devices is proposed.

1.2.2. Optimal capacitor placement in distorted distribution networks

Distribution networks are the main pool of power network losses, and capacitors are a viable tool to reduce losses by compensating load reactive currents. Furthermore, capacitors provide other benefits, such as voltage profile improvement, network stability enhancement, and capacity release of network devices [28]. To reach these benefits, proper methods are needed to determine the optimal locations and sizes of capacitors in distribution networks. Optimal allocation of capacitors in non-distorted distribution networks is a well-researched field [7,28–33], while for distorted networks the problem is challenging and still open to further researches.

With the increasing prevalence of nonlinear loads in distribution networks, it has become necessary to consider harmonic interactions into account when determining the optimal allocation of capacitors. The allocation of capacitors in distorted distribution networks has been investigated in several studies, with various considerations presented in Table 3. Recent approaches have been categorized based on the optimization criterion, optimization method, Harmonic Power Flow (HPF) method, and load modeling of the network.

The cost of capacitors and network losses are typically the primary parameters in the optimization criterion for recent approaches in power system applications. Various optimization algorithms are utilized to solve the allocation problem, with evolutionary algorithms being more favored in recent years. The most practiced HPF method is Harmonic Penetration (HP), contrasting with the Complete Harmonic Load Flow (CHLF) method.

1.2.3. Application of combined APFs and capacitors in distorted distribution networks

The integration of capacitors and APFs in power distribution systems has been an increasing concern in recent years. This combination has high potential for tackling power quality issues, especially those involving harmonics and resonance occurrences. Important research on the subject published recently can be cited. [51] proposed a method to calculate voltage of the capacitors incorporated in shunt APFs. this method helps to prevent overvoltage and related accidents. Reference [52] carried out a thorough investigation on deployment of capacitors, photovoltaic distributed generators (PVDGs), and fault current limiters in distribution networks to reduce harmonic distortion, losses and fault currents. The research used PVDGs to inject active power and compensate harmonic currents, resulting in power efficiency and harmonic reduction. [53] presented a comprehensive shunt virtual-damping-based strategy for suppressing external loop amplification and self-excited oscillation of APFs to prevent resonance threats on the security and stability of power distribution networks. In [54], a framework for analyzing the effect of resonance caused by shunt capacitors in the operation of APFs was presented. [55] presented a control Lyapunov-based algorithm for Active Power Filters (APFs) to effectively control and mitigate harmonics in electric vehicle-incorporated networks under various load conditions and network disturbances. The utilization of the proposed Lyapunov-based algorithm eliminates the need for capacitors as high-pass or low-pass filters. Authors in [56] investigated the advantages of combining energy storage systems with supercapacitors and APFs for harmonics correction in microgrids. The research revealed the possibility of improving electricity quality and grid resilience. In [57] an APF based on a switched-capacitor multilevel inverter is presented as a solution to address power quality issues such as harmonics, voltage swell, and voltage unbalance. In [58], a comprehensive review was conducted on the topologies and technologies of APFs in the presence of solar and wind distributed generation. The review specifically identified split capacitor configurations as a promising technique for advanced APF apparatuses. In the work [59], a unique control method for APFs that adapts their operation based on load situations and harmonic levels was proposed, enhancing overall system performance. In [60], a multi-objective approach is introduced for the control of APFs in harmonic compensation. The proposed approach aims to achieve a balance in capacitor voltage and achieve complete harmonic reference, thereby ensuring compliance with grid standards. [61] presented a modified indirect extraction method for reducing the size of the DC-link capacitor in a single-phase APF. [62] introduced a method based on the instantaneous reactive power theory to determine the capacitor parameters in APFs.

While numerous studies have examined the combined operation of APFs and capacitors, there is a noticeable gap in the literature concerning the optimal simultaneous allocation of APFs and capacitors.

1.3. Problem description

In distribution networks, both APFs and capacitors can enhance power quality by mitigating harmonic pollution and improve power efficiency by reducing network losses.

This paper presents a novel simultaneous approach for optimizing the utilization of both APFs and capacitors. The contribution of the paper is focused on harmonic mitigation and loss optimization in power distribution networks, concurrently. The results of this study are expected to aid network operators in improving harmonic conditions, while optimizing network losses in a practical and easy-to-implement manner.

1.4. Paper organization

The remainder of this paper is structured as follows. Section 2 details the HPF method and its formulation. Section 3 outlines the proposed optimization approach, which utilizes the PSO algorithm. The procedure of this approach is illustrated in this section. Section 4 presents the numerical results, while Section 5 discusses the concluding remarks.

2. Harmonic power flow

The calculation of harmonic voltages and currents in power networks can be accomplished using the Harmonic power flow. Harmonic power flow methods are generally categorized into two groups: methods based on time-domain analysis and methods based on frequency-domain analysis. Time-domain methods use numerical approaches to determine the network's differential equations, while in frequency-domain methods the Conventional Load Flow (CLF) approaches are developed to incorporate both fundamental and harmonic frequencies. In recent research, frequency-domain methods have gained popularity due to their computational efficiency compared to time-domain methods, which require extensive calculations [63].

There are several frequency-domain methods proposed in the literature. Some methods, such as complete harmonic load flow [64], iterative harmonic penetration [65] and simplified harmonic load flow [66] determine harmonic voltages and currents for all harmonics in a coupled manner, while other frequency-domain methods, such as harmonic penetration, disregard the harmonic correlations and solve harmonic power flow for each harmonic individually. Coupled methods require precise information about nonlinear loads, which can be impractical due to the large number of such loads in distribution networks. Compared to alternative methods, HP offers several advantages, including reduced complexity, faster response times, and lower data requirements, while still providing satisfactory accuracy in determining the harmonic state of the network. Although it may be slightly less accurate than other methods, its benefits, particularly its fast response, make it particularly well-suited for optimization problems requiring multiple HPF iterations [67].

In this paper, the harmonic penetration method is employed to assess the harmonic condition of the network. In this method, firstly, a conventional power flow is executed to determine the fundamental frequency condition of the network regarding nonlinear loads, considering them as PQ (constant power, constant reactive power) buses. Subsequently, the harmonic current of nonlinear loads for each harmonic (i_{nb}^{h}) is determined applying equation (1), which has been proposed in various studies [38,39,42,68].

$$i_{nb}^{h} = c(h) \bullet i_{nb}^{1} \tag{1}$$

In the above context, the term $c(h)$ represents the current injection factor, which can be determined by conducting field tests or Fourier analysis [37–39,42,67]. The term i_{nb}^{1} refers to fundamental frequency component of the nonlinear loads current, which can be calculated from the conventional load flow results using equation (2).

$$i_{nb}^{1} = \left(\frac{P_{nb} + i \bullet Q_{nb}}{V_b^1}\right)^{*} \tag{2}$$

where P_{nb} and Q_{nb} are active and reactive power of the corresponding nonlinear load and V_b^1 is the nonlinear load's voltage magnitude in the fundamental frequency calculated by CPF.

To determine the harmonic voltages, the nonlinear loads are considered as current sources, and the node voltage method is employed with the assistance of the admittance matrix for each harmonic. The construction of the admittance matrix is yield based on the harmonic modelling of linear components for each harmonic. Neglecting the skin effect, the admittances of compensating capacitors, network branches and linear loads can be represented by equations (3)-(5) as follows

$$y_{cb}^{h} = h \bullet y_{cb}^{1} \tag{3}$$

$$y_{b,b+1}^{h} = \frac{1}{r_{b,b+1} + i \bullet h \bullet x_{b,b+1}} \tag{4}$$

$$y_{lb}^{h} = \frac{P_{lb}}{\left|V_b^1\right|^2} - i\frac{Q_{lb}}{h \bullet \left|V_b^1\right|^2} \tag{5}$$

where y_{cb}^{1} and y_{cb}^{h} are the capacitors admittance in the 1st and h^{th} harmonic orders respectively, $r_{b,b+1}$ and $x_{b,b+1}$ are resistance and reactance of the branch b to $b+1$, $y_{b,b+1}^{h}$ is the corresponding admittance of the branch b to $b+1$ in harmonic h, P_{lb} and Q_{lb} are active and reactive power of linear loads, and y_{lb}^{h} is the linear load corresponding admittance at harmonic h.

Hence, the admittance matrix for each harmonic is constructed according to the following formula:

$$Y_{a,b}^{h} = \begin{cases} -y_{a,b}^{h} if a \neq b \\ y_{a-1,b} + y_{a+1,b} + y_{cb}^{h} + y_{lb}^{h} if a = b \end{cases} \tag{6}$$

Here, $y_{a-1,b}$ and $y_{a+1,b}$ represent the admittances of all the lines linked to bus b relying on the network configuration.

Employing the node voltage analysis technique, the harmonic voltages ($\boldsymbol{V^h}$) can be obtained as follows:

$$\boldsymbol{V}^{h} = \left(\boldsymbol{Y}^{h}\right)^{-1} \bullet \boldsymbol{I}^{h} \tag{7}$$

In this equation, $\boldsymbol{Y^h}$ represents the admittance matrix for harmonic h, and $\boldsymbol{I^h}$ is the harmonic injection current of nonlinear loads.

Ultimately, upon calculating the voltages of all harmonics in the network, the voltage distortion factors including THD and IHD can be evaluated using equations (8) and (9), respectively.

$$THD_b = \left[\frac{\sqrt{\sum_{h=3,5,\cdots,H} \left|v_b^h\right|^2}}{\left|v_b^1\right|}\right] \tag{8}$$

$$IHD_b^h = \frac{\left|v_b^h\right|}{\left|v_b^1\right|} \tag{9}$$

Voltage THD quantifies the overall deviation of the voltage waveform from its ideal sinusoidal shape. On the other hand, IHD refers to the distortion caused by each specific harmonic component, providing information about the amplitude and phase distortion of individual harmonics. Analyzing IHD helps to identify significant harmonic frequencies and to assess their impact on the power system. Monitoring and controlling IHD aids in diagnosing and mitigating harmonic-related issues. Both THD and IHD are vital parameters for evaluating power supply quality and addressing harmonic distortion according to the IEEE 1547 standard.

In the HPF procedure, APFs are modeled as current sources in harmonic frequencies, and their injection current is determined by the optimization method [3]. The injection current of APFs changes the values of vector $\mathbf{I^h}$ in (7), while the presence of capacitors changes $\mathbf{Y^h}$. To simultaneously determine the effect of these devices, the optimization plan determines the injection currents of APFs and the corresponding values of capacitors.

3. Formulation of the problem

In this section, the modeling of the optimal capacitor allocation problem and the optimal allocation of APFs problem in distorted distribution networks are presented, separately. Then, those problems are discussed simultaneously.

3.1. Optimal capacitor allocation in distorted distribution networks

Capacitor placement optimization yields the optimal sizes and locations of capacitors to be installed in the electric network, while considering the optimization criterion and constraints of the problem. Various optimization criteria can be utilized to solve this problem. In this study, the cost of capacitors and the cost of network losses are considered as the optimization criterion, which is expressed in the following equation [46]:

$$C_t = C_{\text{Cap}} + C_{\text{Loss}} \tag{10}$$

The cost of capacitors is considered as C_{Cap} and the cost of network losses is considered as C_{Loss} in the optimization criterion formulation. These costs are calculated using equations (11) and (12), respectively.

$$C_{\text{Cap}} = \sum_{j=1}^{NC} K_j^c \bullet Q_j^c \tag{11}$$

$$C_{\text{Loss}} = K_p \bullet P_{\text{Loss}} = K_p \bullet \sum_{h=1,3,\cdots} P_{\text{Loss}}^h \tag{12}$$

where

j	: installed capacitors index;
NC	: number of installed capacitors;
K_j^C	: cost of capacitors per kVAr ($/kVAr);
Q_j^c	: size of the installed capacitor (kVAr);
h	: harmonic counter;
K_p	: cost of losses per kW ($/kW);
P_{Loss}^h	: network losses in harmonic h (kW);
P_{Loss}	: network total losses (kW).

The constraints of the problem can be classified into two distinct groups: those that are relevant to the network condition, and those that are relevant to the capacitors. Network constraints are defined by the desired operating conditions of the network voltages in fundamental and harmonic frequencies, as described in equations (13)-(15). On the other hand, capacitor constraints prescribe the size of capacitors that should be selected from traditional values and limit the total installed kVAr below the reactive demand of the network. These constraints are formulated in equations (16) and (17) [9,48,39].

$$V^{\min} \le V_b^{\mathrm{RMS}} \le V^{\max}, \text{for } b = 1,2,\cdots,NB \tag{13}$$

$$THD_b \le THD^{\max}, \text{for } b = 1,2,\cdots,NB \tag{14}$$

$$IHD_b^h \le IHD^{\max}, \text{for } b = 1,2,\cdots,NB; h = 3,5,\cdots,H \tag{15}$$

$$Q_j^c \in \Omega_{\mathrm{Cap}}, \text{for} j = 1,2,\cdots,NC \tag{16}$$

$$\sum_{j=1}^{NC} Q_j^c \le Q_{\mathrm{sys}} \tag{17}$$

where

b	: bus counter;
V_b^{RMS}	: voltage RMS value of the bus b;
$V^{\min}$	: minimum permissible value of the voltage RMS;
$V^{\max}$	: maximum permissible value of the voltage RMS;
THD_b	: voltage THD of the bus b;
$THD^{\max}$	: maximum permissible value of the voltage THD;
IHD_b^h	: voltage IHD of the bus b in harmonic h;
$IHD^{\max}$	: maximum permissible value of the voltage IHD;
Ω_{Cap}	: standard capacitor sizes;
Q_{sys}	: total reactive demand of the network.

3.2. Allocation of APFs in distorted distribution networks

The optimal allocation of APFs involves determining their optimal location, size, and injection current. The optimization criterion is typically related to the cost of APFs, which is proportional to their size. Therefore, many studies aim to minimize the APFs injection currents. In this paper, the optimization criterion is the total cost of APFs, which is calculated based on equation (18) [18,5,2].

$$C_t = C_{APFs} = \sum_{i=1}^{NA} C\left(S_i^{\mathrm{APF}}\right) \tag{18}$$

where the variables NA, S_i^{APF} and $C\left(S_i^{\mathrm{APF}}\right)$ refer to the number of installed APFs, the size of the i-th APF, and the cost of the i-th APF, respectively. The cost of each APF is calculated using equation (19).

$$C\left(S_i^{APF}\right) = C^{\mathrm{fix}} + C^{\mathrm{var}}.S_i^{\mathrm{APF}} \tag{19}$$

where C^{fix} and C^{var} are the parameters for fixed and variable costs associated with the APFs.

APFs are known to improve the state of harmonic distortion within the network, while having minimal impact on the fundamental frequency condition. Thus, the effect of APFs on the RMS value of the network voltages can be neglected when formulating the constraints of the APF allocation problem. However, it is essential, to ensure that the RMS value of the network voltages remains within acceptable ranges. Additional constraints of the problem encompass restricting the voltage distortion factors (THD and IHD) to be below the permissible thresholds, as defined in equations (20) and (21). Additionally, the RMS value of each APF injection current must be less than the size of the corresponding APF, as specified in equation (22). Finally, the size of APFs must be selected from a set of common values, as specified in equation (23) [18,17,15].

$$THD_b \le THD^{\max}, \text{for } b = 1,2,\cdots,NB \tag{20}$$

$$IHD_b^h \le IHD^{\max}, \text{for } b = 1,2,\cdots,NB; h = 3,5,\cdots,H \tag{21}$$

$$i_i^{rms} \le S_i^{\mathrm{APF}}, \text{for } i = 1,2,\cdots,NA \tag{22}$$

$$S_i^{APF} \in \Omega_{APF}, \text{for } i = 1,2,\cdots,NA \tag{23}$$

where

i_i^{rms}	: RMS value of the APF injection current;
Ω_{APF}	: Set of APFs standard sizes.

3.3. Optimal simultaneous allocation of capacitors and APFs

The solution to the simultaneous problem involves determining the optimal sizes and locations of both capacitors and APFs, as well as the injection currents of APFs. As such, the decision variables that need to be considered include:

- Size and location of capacitors
- Size and location of APFs, in addition to the injection current of the APFs

It is worth noting that while the sizes and locations of capacitors and APFs are discrete variables, the injection current of APFs is continuous. To address this issue in the optimization procedure, a two-part particle representation is used in the PSO. This approach is further discussed in the next section.

The costs associated with the problem include the cost of the installed devices and the cost of power losses. The former includes the cost of both APFs and capacitors, which are installed to reduce network losses and improve the harmonic condition of the network. The corresponding cost of network losses can be included in the optimization criterion. At the same time, improving the harmonic condition can help to ensure that the network meets its operational allowable ranges. As such, the optimization criterion will include the cost of both capacitors and APFs, as well as the cost of power losses in the network, which can be expressed using equation (24).

$$C_t = C_{Cap} + C_{Loss} + C_{APFs} \tag{24}$$

The constraints of the simultaneous problem include all of the constraints defined in the above particular problems, as outlined in equations (25)-(31). Specifically, constraint (25) pertains to the voltage profile of the network, while constraints (26) and (27) pertain to the harmonic condition of the network. Constraints (28) and (29) are related to the size of capacitors and the total amount of reactive compensation, respectively. Finally, constraints (30) and (31) are related to the size of the APFs. Together, these constraints ensure that the simultaneous allocation of capacitors and APFs satisfies the necessary conditions for optimal network performance.

$$V^{\min} \le V_b^{\mathrm{RMS}} \le V^{\max}, \text{for } b = 1,2,\cdots,NB \tag{25}$$

$$THD_b \le THD^{\max}, \text{for } b = 1,2,\cdots,NB \tag{26}$$

$$IHD_b^h \le IHD^{\max}, \text{for } b = 1,2,\cdots,NB; h = 3,5,\cdots,H \tag{27}$$

$$Q_j^c \in \Omega_{\mathrm{Cap}}, \text{for} j = 1,2,\cdots,NC \tag{28}$$

$$\sum_{j=1}^{NC} Q_j^c \le Q_{\mathrm{sys}} \tag{29}$$

$$i_i^{rms} \le S_i^{\mathrm{APF}}, \text{for } i = 1,2,\cdots,NA \tag{30}$$

$$S_i^{APF} \in \Omega_{APF}, \text{for } i = 1,2,\cdots,NA \tag{31}$$

4. Optimization procedure

In this paper, the PSO algorithm is utilized to solve the MINLP simultaneous allocation problem of both APFs and capacitors. To do so, each particle in the PSO algorithm is divided into two parts. The first part represents the capacitors and contains NCC cells, corresponding to the quantity of candidate locations for installing capacitors. Each cell in this part includes a number indicating the size of the capacitor to be installed at the respective candidate location. The second part of the particle is more significant, and contains 2•H cells for each candidate bus. Thus, the final size of the second part is 2•NCA•H, where NCA is the number of candidate locations for installing APFs and H is the number of harmonic orders. Each cell in the second part represents either the real or imaginary part of the injection current in a specific harmonic order at a specific candidate location. For example, Fig. 1 shows a particle with four capacitor candidate locations, five available sizes of capacitors (illustrated in Fig. 2), two APF candidate locations, and two harmonic orders (i.e., fifth and seventh harmonic orders). The resulting network condition for this particle is illustrated in Fig. 2 for a typical distribution network. In this typical example, the size of APFs is assumed as a multiple integer of 1% of the network base current and is limited to 15%. The standard set of available capacitors is shown in Fig. 2. where 5 types of capacitors with sizes 500 kVAr, 750 kVAr, 1000 kVAr, 1250 kVAr and 1500 kVAr are available.

Sizes of the capacitors can be directly determined by the particle containing a number, but the size of the APFs cannot be determined directly, as it is dependent on the RMS value of the APF's injection current. To determine the appropriate size of the APFs, the criterion is choosing the least standard size larger than the RMS value of the injection current. The RMS value of the injection current of an APF is calculated using the following equation:

$$i_i^{\mathrm{RMS}} = \sqrt{\sum_{h=3,5,\cdots,H} \left({i_{r,i}^{h}}^2 + {i_{j,i}^{h}}^2\right)} \tag{32}$$

where $i_{r,i}^h$ and $i_{j,i}^h$ represent the real and imaginary components of the injection current of the i-th APF in the h-th harmonic, respectively. For the APF1 placed on ACL1 in Fig. 2, the RMS value of the injection current can be calculated as:

$$i_{APF1}^{\mathrm{RMS}} = \sqrt{\left(0.075^2 + 0.063^2\right) + \left(0.053^2 + 0.045^2\right)} = 0.12012pu = 12.012\%$$

The size of this APF should be chosen as the least standard size larger than 12.012, that is, 13%. The corresponding cost can be calculated as below, being dependent on C^{fix} and C^{var}.

$$C(APF1) = C^{\mathrm{fix}} + C^{\mathrm{var}} \times 13$$

Calculating the cost of the other APF (located on ACL2) with the same formulation will yield the cost of APFs (C_{APFs}), which is the sum of the cost of both APFs. The size of APF2 is 6%.

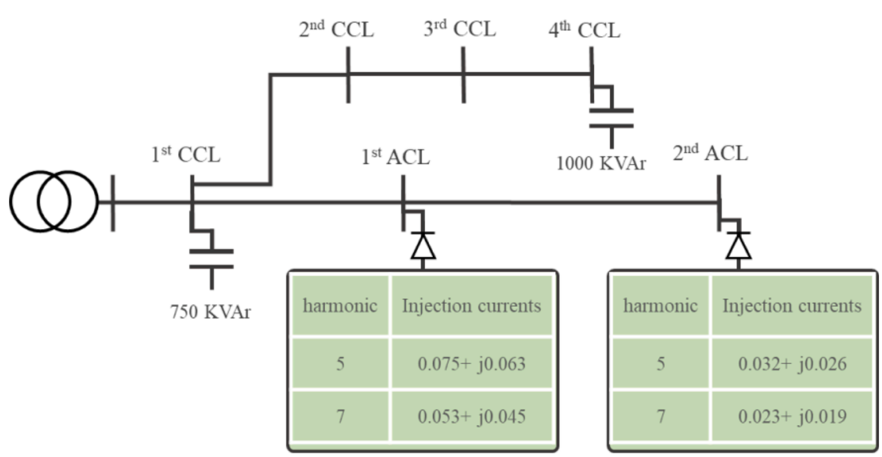
In the PSO algorithm, each particle approaches the optimum solution through its present velocity, and past individual and group experiences. Each particle is represented by its position (X_i^k), which is updated to (X_i^{k+1}) using the particle velocity (V_i^{k+1}) regarding its last iteration velocity (V_i^k), the best position experienced by the particle ($Pbest_i^k$) and the best position experienced by the whole population ($Gbest^k$), according to the following equations [69,70]:

$$V_i^{k+1} = \omega V_i^k + c_1 \bullet r_1 \bullet \left(Pbest_i^k - X_i^k\right) + c_2 \bullet r_2 \bullet \left(Gbest^k - X_i^k\right) \tag{33}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{34}$$

2	0	0	3	0.075	0.063	0.053	0.045	0.032	0.026	0.023	0.019
1st CCL	2nd CCL	3rd CCL	4th CCL	real	Image	real	Image	real	Image	real	Image
				5th harmonic		7th harmonic		5th harmonic		7th harmonic	
				1st ACL				2nd ACL			

Fig. 1. Structure of the proposed particles containing a typical example (CCL: Capacitor Candidate Location, ACL: APF Candidate Location).



Set of available standard sizes of capacitors

500 kVAr	750 kVAr	1000 kVAr	1250 kVAr	1500 kVAr
1	2	3	4	5

Fig. 2. Network resulting condition for the particle shown in Fig. 1 in a typical distribution network (CCL: Capacitor Candidate Location, ACL: APF Candidate Location).

where k is the iteration number, ω, c_1, c_2 are weight parameters, and r_1, r_2 are randomly generated values within the range of 0 to 1. Following the update of the particle positions, certain modifications are required due to the presence of discrete and continuous components within the particles. Specifically, the portion of the particles that pertains to the capacitor condition undergoes rounding in each iteration to yield discrete variables. Conversely, the segment of the particles associated with the injection current of APFs is not subjected to rounding, but is instead restricted to the maximum permissible magnitude by reducing the injection currents across all harmonics in case of size violation.

During each iteration, particles are evaluated using the following fitness function:

$$F = C_t + P_1\left[\sum_{b=1}^{NB}\max(0, THD_b - THD^{\max})\right] + P_2\left[\sum_{b=1}^{NB}\sum_{h=3,5,\cdots}\max\left(0, IHD_b^h - IHD^{\max}\right)\right] + P_3\left[\sum_{b=1}^{NB}\left(\max\left(0, V_b^{RMS} - V^{\max}\right) - \min\left(0, V_b^{RMS} - V^{\min}\right)\right)\right] + P_4 \bullet \max\left(0, \sum_{j=1}^{NC} Q_j^c - Q_{sys}\right) \tag{35}$$

where C_t is calculated from (24) and P_1, P_2, P_3 and P_4 are penalty factors.

Some constraints are incorporated into the evaluation procedure described in (35), while others are addressed through modifications to the particles' positions, to ensure compliance with defined acceptable ranges.

After evaluating all particles in each iteration, the Pbests and Gbest are updated based on the fitness function. The program then proceeds to the next iteration until the maximum number of iterations is reached. The PSO key parameters are determined by sensitivity analysis technique, and the specific values for each case study are provided in their respective sections. Fig. 3 illustrates the flowchart of the proposed optimization procedure.

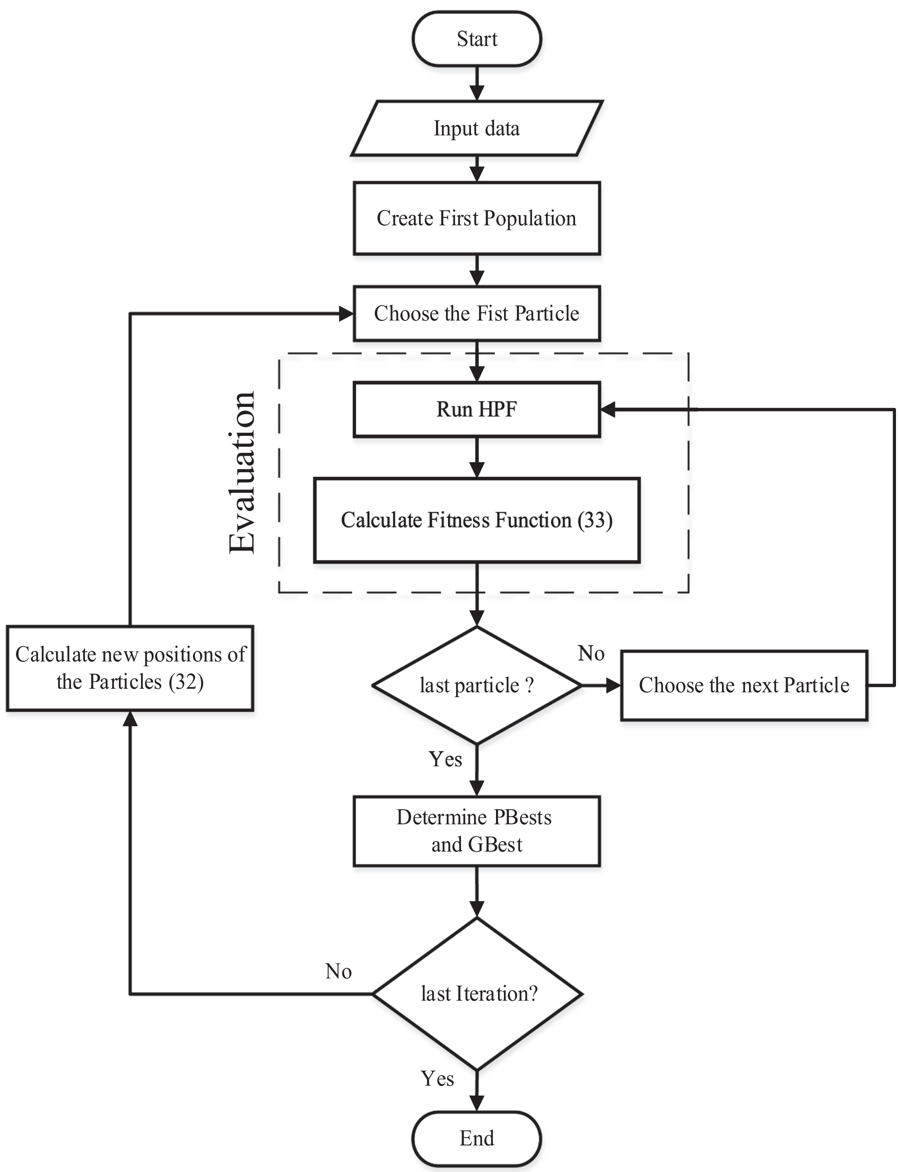


Fig. 3. Flowchart of the proposed optimization procedure.

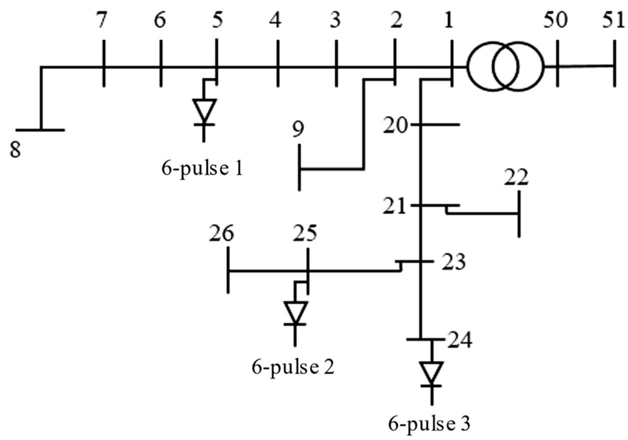


Fig. 4. The IEEE 18-bus test network [4].

5. Numerical results

Simulation tests were performed on the IEEE 18-bus test network depicted in Fig. 4, using MATLAB 2019b. The harmonic loads were modeled as 2.7 MW six-pulse converters, and their corresponding harmonic injection factors are shown in Fig. 5. The harmonic penetration method was utilized as the harmonic power flow tool, the voltage harmonic constraints were based on the IEEE-519 standard, with maximum allowable values for THD and IHD set at 5% and 3%, respectively. The allowable range for the RMS value of the network voltages was set between 0.9 pu and 1.1 pu.

The sizes of the APFs are integer multiples of 1% pu and are limited to 12% pu (base voltage is 12.5 kV and base power is 10 MVA). The C^{fix} and C^{var} are $22,500 and $180,000/pu, respectively. Standard available sizes of capacitors and their relating cost factors are presented in Table 4, and the cost factor of the network losses is considered equal to 168 $/kW [37].

Three case studies were conducted on the IEEE 18-bus test network. In the first study, capacitors were allocated without considering the harmonic constraints, and then APFs were used to address the harmonic issues of the network. In the second study, capacitors were allocated with consideration of the harmonic limits, and APFs were employed to improve the harmonic condition of the network and to ensure that voltage harmonic factors remained within the allowable range. Finally, in the third study, capacitors and APFs were simultaneously allocated to address the constraints of the problem and to optimize network losses concurrently. Detailed information regarding each case study is presented in the subsequent sections.

5.1. First Study: Optimal capacitor placement, followed by optimal APF allocation

In this study, the objective is to allocate capacitors to optimize network losses and improve the voltage profile without considering the harmonic constraints. Subsequently, optimal APFs are utilized to maintain the harmonic constraints of the network.

5.1.1. Optimal allocation of capacitors with no regard to harmonic constraints

The number of iterations and size of the population are set to 200 and

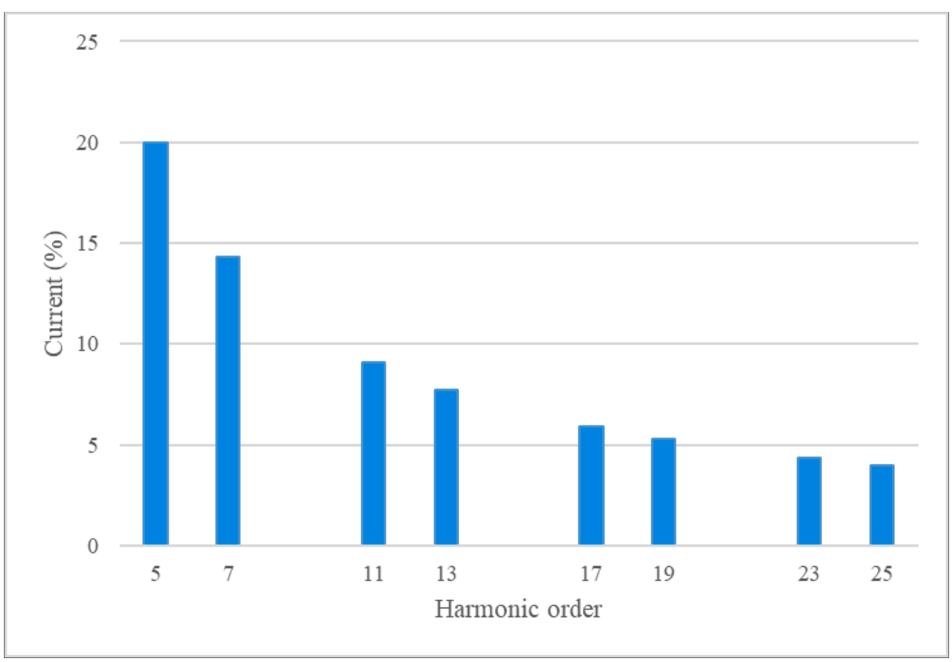


Fig. 5. Harmonic spectra of six-pulse converters.

Table 4
Size and cost factor of available capacitors.

$Q^c(kVAr)$	150	300	450	600	750	900	1,050	1,200	1,350
$k^c(\$/kVAr)$	5	3.5	2.53	2.2	2.76	1.83	2.28	1.7	2.07
$Q^c(kVAr)$	1,500	1,650	1,800	1,950	2,100	2,250	2,400	2,550	2,700
$k^c(\$/kVAr)$	2.01	1.93	1.87	2.11	1.76	1.97	1.7	1.89	1.87
$Q^c(kVAr)$	2,850	3,000	3,150	3,300	3,450	3,600	3,750	3,900	4,050
$k^c(\$/kVAr)$	1.83	1.8	1.95	1.74	1.88	1.7	1.83	1.82	1.79

Table 5
Optimal solution of the optimal capacitor allocation problem in the first study.

Size and location of installed Capacitors (pu)	Total installed kVAr	Min V (pu)@ bus	Max V (pu)@ bus	Max THD (%)
$Q^4 = 0.24$ $Q^7 = 0.12$ $Q^{23} = 0.21$ $Q^{25} = 0.12$	$Q^t = 0.69$	0.977@ 26	1.05@ 50	10.54
Max IHD (%)	**Loss (kW)**	**Cost of Capacitors ($)**	**Total Cost ($)**	**Profit ($)**
9.46	967	13,896	178,264	40,872

500 by sensitivity analysis that is not reported due to brevity, and all network buses are assumed as candidate locations in the optimization procedure. The optimal solution is listed in Table 5, which improved network losses to 967 kW, corresponding to a reduction equal to 326 kW. The profit is calculated by comparing the cost of network losses before optimization and the total cost of the final solution.

The voltage profile of the network is presented in Fig. 6, which shows that the utilization of optimal capacitors has improved the voltage profile of the network, maintaining it within the allowable ranges. The network voltages THD factor is shown in Fig. 7, which indicates an improvement in the harmonic condition of the network due to the natural behavior of capacitors in filtering harmonic currents. However, despite this improvement, the network condition is not yet satisfactory, as the maximum IHD of the network voltages is 9.46% at the fifth harmonic on bus 25.

5.1.2. *Optimal allocation of APFs*

To satisfy the harmonic constraints of the network, the optimization procedure was carried out using optimal APFs' allocation. For this test, the number of iterations and population size were set to 150 and 200, respectively. The outcomes of the optimization process are detailed in Table 6, which shows that two APFs with a total size of 12 were utilized to handle the harmonic constraints.

Harmonic spectra of the APFs injection current are presented in Fig. 8, where the fifth harmonic has the dominating portion of the injection currents. The network voltages THD factor is illustrated in Fig. 9, showing that all buses are in allowable ranges. Maximum IHD is 3% in bus 7 at the fifth harmonic order.

Table 6
Results of the optimal allocation of APFs in the first study.

Location (Bus)	Size (%)	I^{RMS} (%)	Cost of APF ($)	Max THD (%)	Max IHD (%)	Total cost ($)
7	4	3.55	29,700	5	3	66,600
23	8	7.52	36,900			

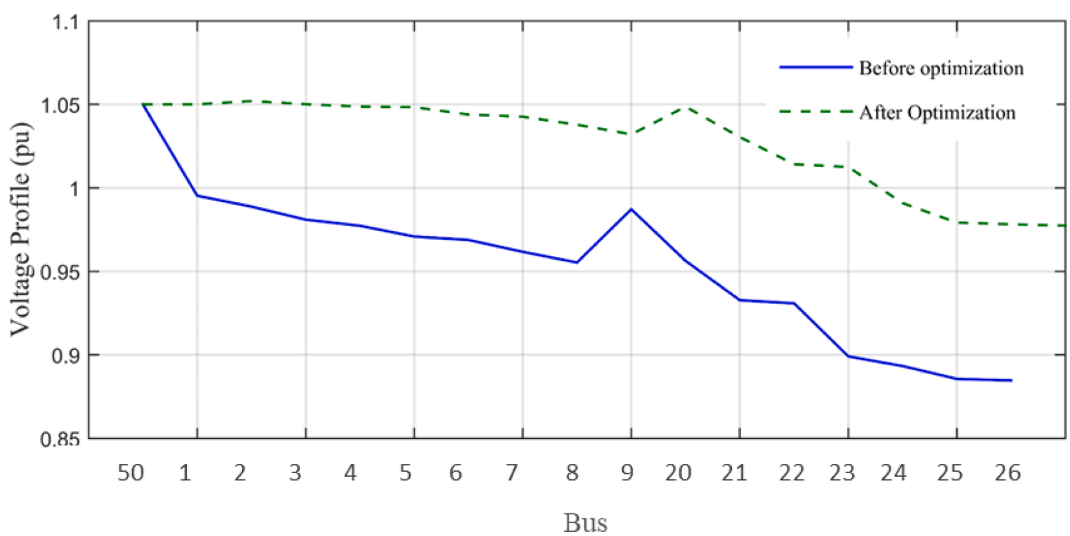


Fig. 6. Voltage profile of the network, before and after optimal capacitor allocation in the first study.

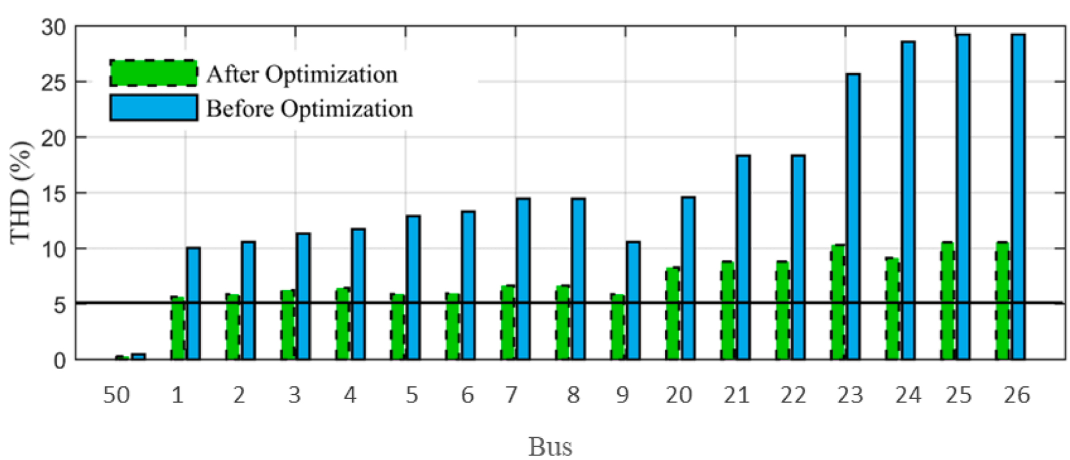


Fig. 7. THD factor of the network voltages, before and after optimal capacitor allocation in the first study.

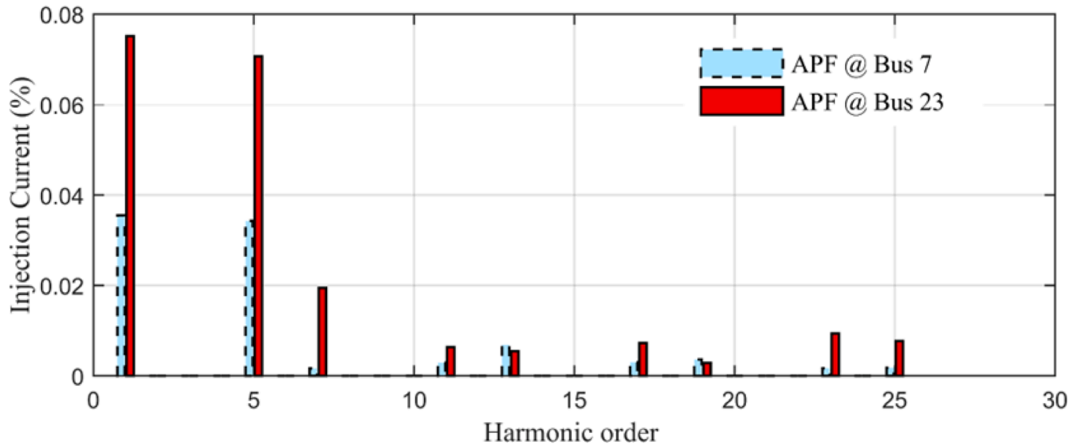


Fig. 8. Harmonic spectra of APFs Injection current.

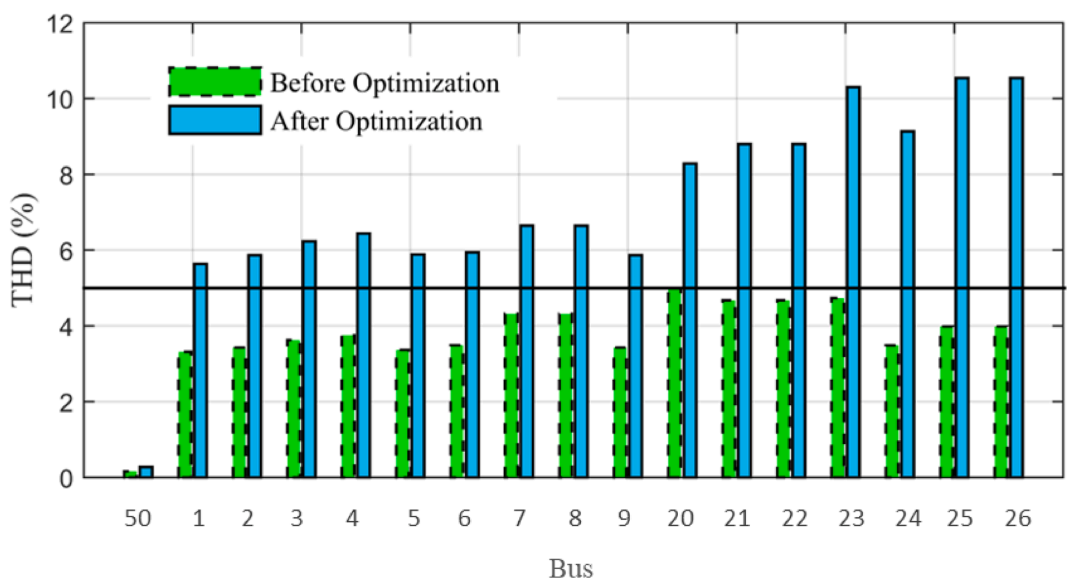


Fig. 9. THD factor of the network voltages, before and after optimal APF allocation in the first study.

5.2. Second Study: The optimal harmonic capacitor placement, followed by optimal allocation of APFs

In this study, the aim of optimal capacitor placement is optimizing network losses with consideration of voltage profile and harmonic (THD, and IHD) constraints. Harmonic constraints are modeled as soft constraints, while other constraints are modeled as hard ones. To perform this subject in the optimization procedure, harmonic penalty factors (P_1 and P_2) are adjusted to be smaller than other penalty factors (P_3 and P_4). This allows the capacitors to effectively reduce the harmonic factors (THD and IHD) of the network without violating other constraints. Following this, the optimal allocation of APFs is performed to satisfy the harmonic constraints of the network further.

Table 7
Optimal solution of the capacitor allocation problem in the second study.

Size and location of installed capacitors (pu)	Total installed kVAr	Min V (pu) @ bus	Max V (pu) @ bus	Max THD (%)
$Q^9 = 0.045$ $Q^{21} = 0.09$ $Q^{23} = 0.24$ $Q^{25} = 0.09$ $Q^{26} = 0.345$	$Q^t = 0.81$	1.01 @ 8	1.05 @ 50	5.95
Max IHD (%)	**Loss (kW)**	**Cost of capacitors ($)**	**Total cost ($)**	**Profit ($)**
5.06	1,283	14,998.5	230,585	−13,319

5.2.1. Optimal capacitor placement considering harmonic constraints

As previously mentioned, capacitors can reduce harmonic pollution due to their natural filtering behavior. Therefore, in this study, the procedure for optimal capacitor allocation considers the harmonic constraints. The number of iterations and population size are set to 200 and 500, respectively, and all network buses are considered candidate locations.

Results of this test are presented in Table 7, demonstrating that considering harmonic constraints in the optimization procedure results in non-profitable solutions for the network. However, there is a significant improvement in the harmonic condition.

Figs. 10 and 11 illustrate the voltage profile and voltage THD factor of the network buses for pre- and post-optimization conditions. The voltage profile of the network buses is maintained within allowable limits after the optimization. However, the voltage THD factor is still out of the allowable limits in some network buses (7, 8, and 26), and the maximum IHD is 5.06% at bus 26 at the fifth harmonic order, which violates the standard limits.

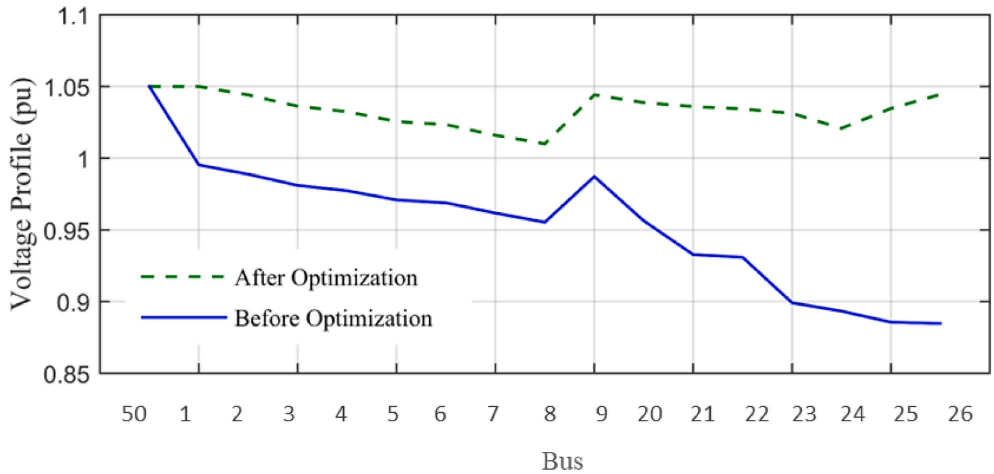


Fig. 10. Voltage profile of the network buses, before and after optimal capacitor allocation in the second study.

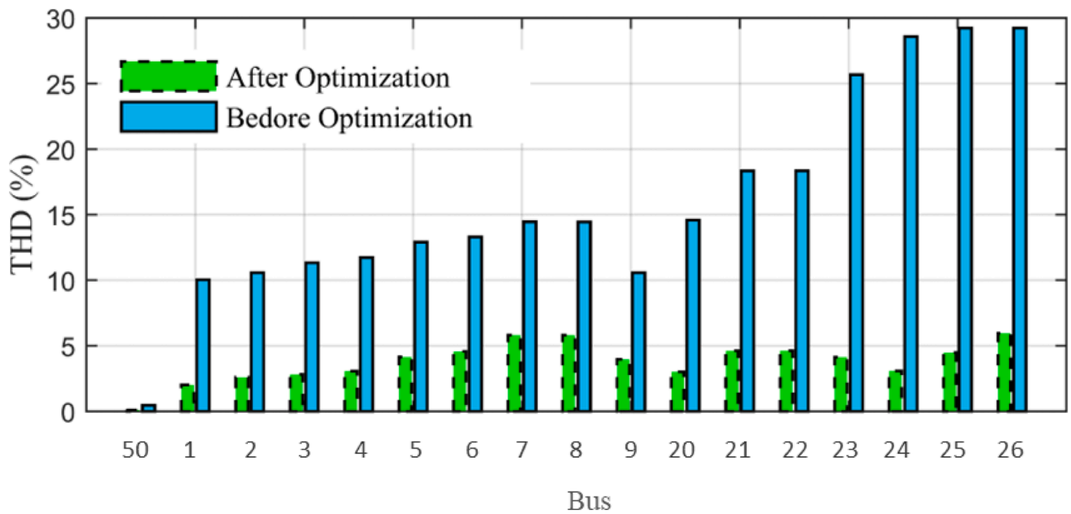


Fig. 11. THD factor of the network voltages, before and after optimal capacitor allocation in the second study.

Table 8
Results of the optimal allocation of APFs in the second study.

Location (Bus)	Size (%)	I^{RMS} (%)	Max THD (%)	Max IHD (%)	Total cost ($)
21	7	6.4	4.99	3	35,100

5.2.2. *Optimal allocation of APFs*

The optimal allocation of APFs was performed with a set number of iterations and population size, resulting in the recommendation of an APF with a size of 7% on bus 21 of the network. The suggested APF size was reduced by 5% when compared to the first study, which can be attributed to the natural filtering behavior of capacitors in reducing harmonic currents. The results are presented in Table 8, showcasing the effectiveness of utilizing both capacitors and APFs in reducing harmonic distortion while optimizing network losses.

The harmonic spectra of the APF injection current are presented in Fig. 12, while the resulting voltage THD of the network buses is illustrated in Fig. 13. It is observed that the maximum voltage IHD is 3% in bus 26 at the fifth harmonic order. The utilization of the APF has significantly improved the harmonic condition and power quality of the network, resulting in voltage THD values that are now within the allowable ranges of the standard.

5.3. *Third Study: Optimal simultaneous allocation of capacitors and APFs*

In this study, the optimal allocation of capacitors and APFs is performed simultaneously, utilizing a population size of 800 and a number of iterations equal to 250. The results of the optimization procedure are presented in Table 9, which suggest the installation of capacitors with a total size of 0.75 pu and one APF with a size of 12%.

Figs. 14 and 15 illustrate the voltage profile and voltage THD factor of the network buses for pre- and post-optimization conditions. The results show that the maximum voltage IHD is 3% at bus 23 in the fifth harmonic order. Installing optimal capacitors and one APF with a size of 12% has improved the network condition to meet the allowable ranges. Furthermore, the harmonic spectra of the APF injection current are presented in Fig. 16, where the fifth harmonic order is dominant.

5.4. *Results comparison*

Fig. 17 depicts the profile of the network voltages for all three studies, showing that all cases maintain the voltages within the desired range of [0.9–1.1] pu. Notably, the highest increase in voltage is observed in case 2, where the total capacitor size is larger than in the others. In Fig. 18, the network voltages THD factor is presented, demonstrating that the three studies could reduce this factor below the allowable limit of 5% specified in the IEEE Std 519.

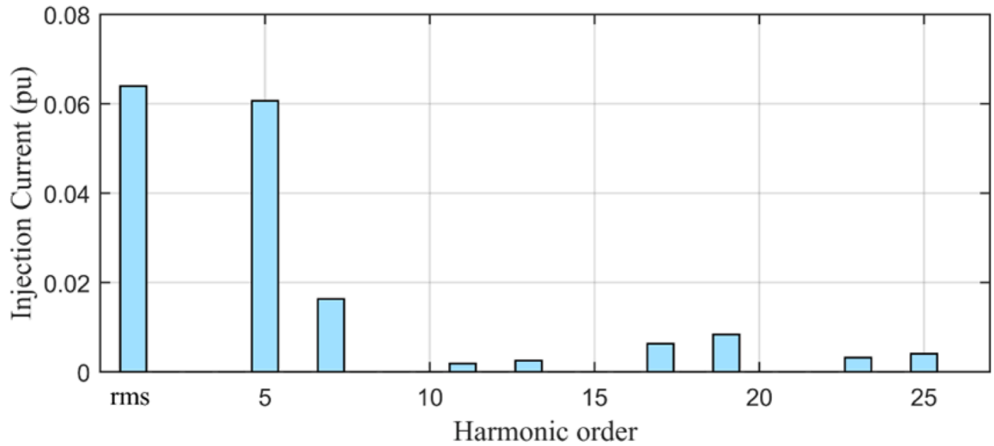


Fig. 12. Harmonic spectra of APF's current in the second study.

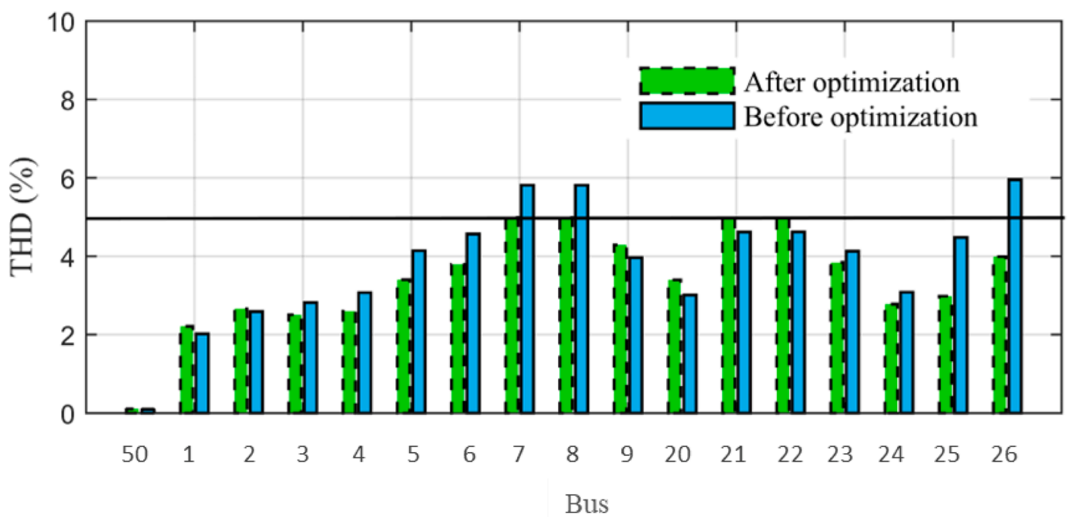


Fig. 13. THD factor of the network voltages, before and after optimal APF allocation in the second study.

Table 9
Optimal solution of the third study.

APF Location (Bus)	Size of APF (%)	Size and location of installed Capacitors (pu)	Total installed kVAr (pu)	Min V (pu) @ bus	Max V (pu)@ bus
23	12	$Q^4 = 0.18$ $Q^9 = 0.09$ $Q^2 = 0.06$ $Q^{21} = 0.12$ $Q^{24} = 0.18$ $Q^{26} = 0.12$	$Q^t = 0.75$	0.972@ 26	1.05 @ 50
Max THD (%)	**Max IHD (%)**	**Loss (kW)**	**Cost of APFs ($)**	**Cost of Capacitors ($)**	**Total Cost ($)**
4.92	3.00	997	44,100	13,779	225,417

Table 10 displays the results regarding the cost associated to the three studies. The findings demonstrate that the third study provides the least expensive solution, indicating the effectiveness of the simultaneous optimization approach. The second most desirable solution is the first study, which shows the effectiveness of capacitors in loss reduction. The proposed solution of the second study has the highest cost, which confirms that it is more economical to utilize capacitors for loss reduction rather than harmonic compensation. Allocating capacitors and APFs simultaneously can enable distribution networks to benefit from both devices and lead to a decrease in system costs.

6. Conclusion

This study proposed a simultaneous optimization approach for the allocation of capacitors and APFs in modern distorted distribution networks. The objective was to optimize the placement and size of capacitors for loss reduction and voltage profile increment, while utilizing APFs to compensate for harmonic currents and reduce harmonic pollution. The capacitors were modeled as shunt reactance in HPF, while the APFs were modeled as current sources. The optimization plan determined the optimal locations, sizes, and injection currents of APFs.

The PSO algorithm was used as the optimization tool, with a specific two-part structure for particles. The first part determined the corresponding size and location of capacitors, while the second part determined the injection current and location of APFs. The size of APFs was dependent on the total RMS current of filters.

A comprehensive analysis was conducted on the IEEE 18-bus test network, using MATLAB 2019b, with a primary focus on addressing harmonic issues, voltage constraints, and optimizing network losses. Three meticulous case studies were performed to investigate different

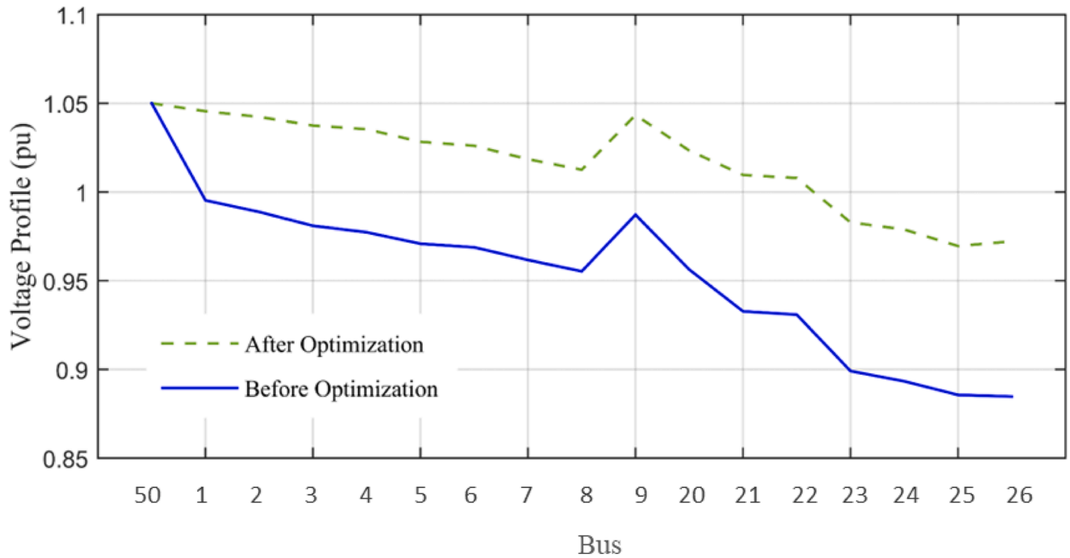


Fig. 14. Voltage profile of the network buses, before and after optimization in the third study.

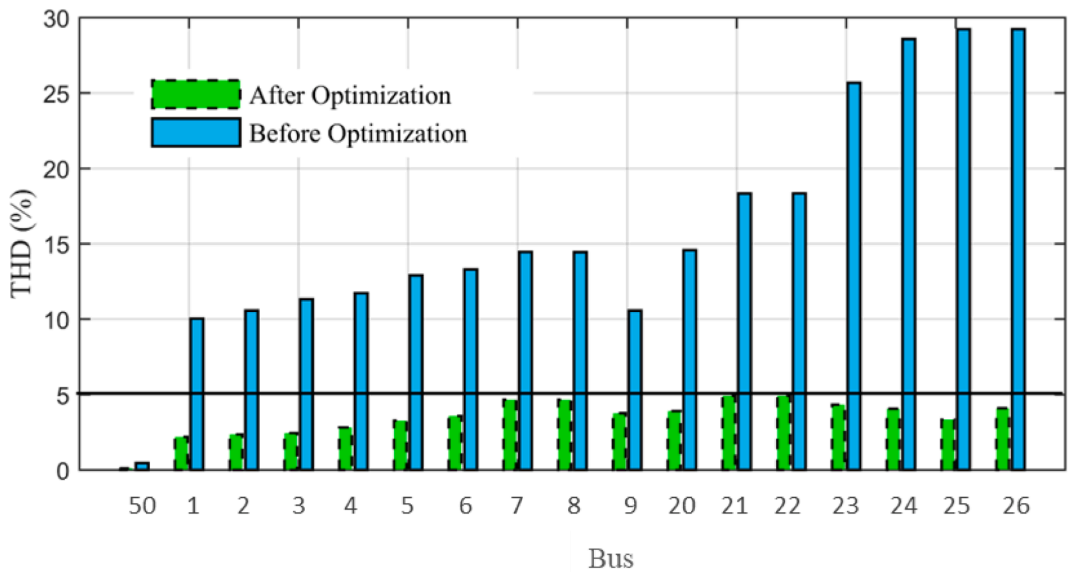


Fig. 15. THD factor of the network voltages, before and after optimization in the third study.

approaches. In the first study, optimal capacitor placement took precedence, resulting in a significant reduction in network losses by 326 kW, an improved voltage profile within the acceptable range of 0.9 pu to 1.1 pu, and a reduction in THD. However, the maximum IHD remained unsatisfied at 9.46% on bus 25 at the fifth harmonic. In the second study, capacitors were allocated while considering harmonic limits, leading to enhanced voltage profiles and reduced THD, yet some buses exceeded the constraints, with a peak IHD of 5.06% on bus 26. The third study introduced a simultaneous allocation approach of capacitors and APFs, yielding a cost-effective solution with reduced network losses, well-maintained voltage profiles, and full compliance with all constraints. Remarkably, the third study proved to be the most cost-effective strategy with the total cost of $225,417, which is $16,566 lower than the second most suitable solution, underscoring the significant potential of the simultaneous allocation of capacitors and APFs for optimizing power distribution systems, while ensuring compliance with diverse constraints. This integrated approach promises to enhance overall network performance and efficiency, offering valuable insights for future power system optimization endeavors in finding optimal solutions for power quality improvement and loss reduction.

Future research endeavors will focus on advancing the employed optimization techniques. Specifically, we will explore the utilization of multi-objective optimization to simultaneously allocate APFs and capacitors. This approach will consider additional objectives, such as cost-effectiveness, system reliability, and environmental impact, providing a more comprehensive framework for decision-making.

Furthermore, future investigations will emphasize the integration of uncertainties and dynamic factors into the optimization process. By accounting for these variables, we can enhance the efficiency and effectiveness of power distribution systems, leading to more robust and reliable solutions.

The findings of this study hold significant practical implications for network operators, as they provide valuable insights into optimal strategies for power quality enhancement and loss reduction. The proposed approach, coupled with future advancements, will assist operators in making informed decisions regarding the allocation of capacitors and APFs.

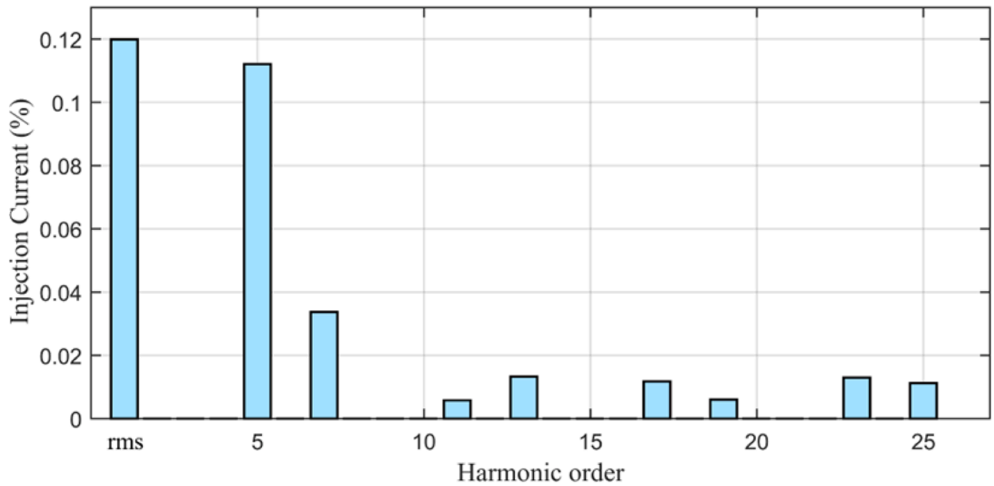
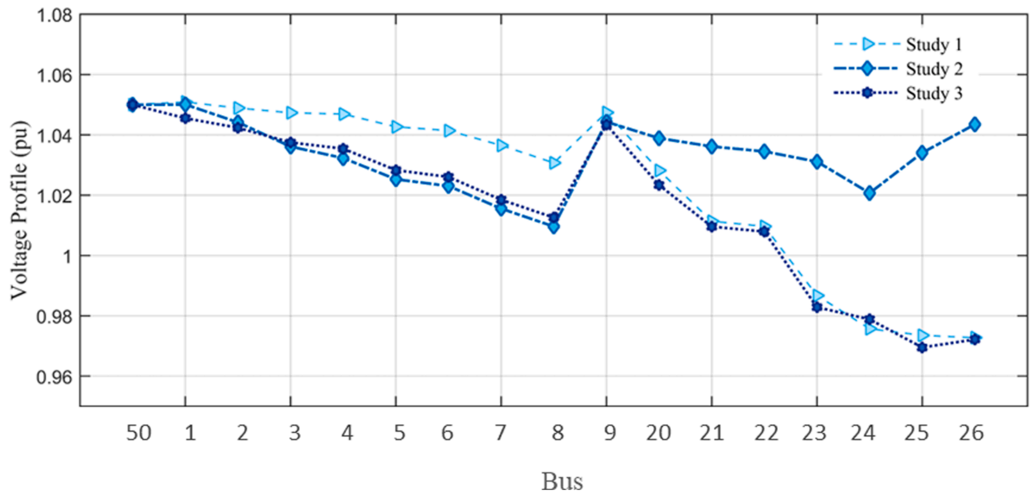
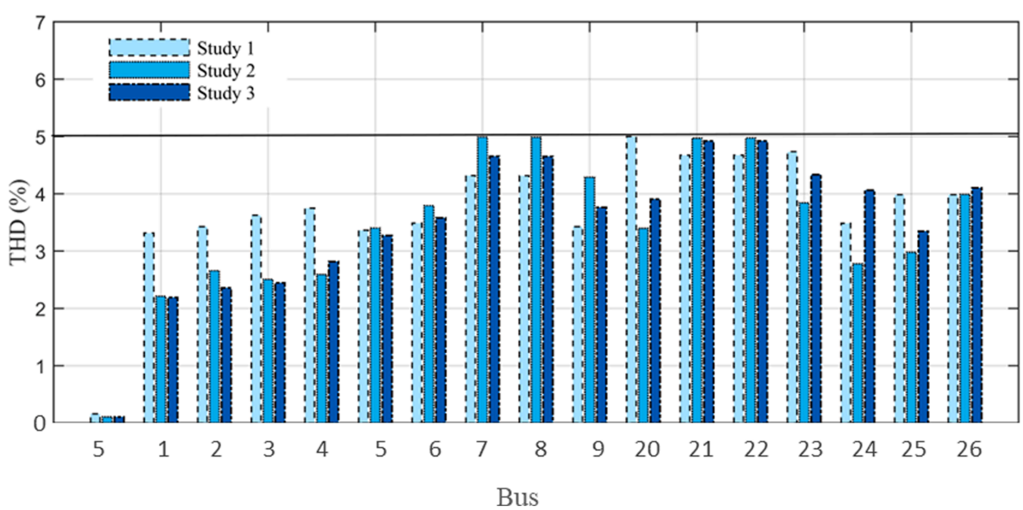


Fig. 16. Harmonic spectra of APF injection current in the third study.



Voltage profile of the network voltages in the three studies.



Voltage THD factor in all the three studies.

Table 10
Final comparison of cost results of the studies.

Study	Procedure		Cost of capacitors ($)	Cost of APFs ($)	Loss (kW)	Total cost ($)
1	CCP[1]	AAPF[2]	13,896	66,600	961	241,983
2	HCP[3]	AAPF	14,999	35,100	1,279	264,942
3	SACAPF[4]		13,779	44,100	997	225,417

CCP: Conventional Capacitor Placement with no regard to harmonic constraints.
AAPF: Allocation of APFs.
HAC: Harmonic Capacitor Placement (capacitor placement considering harmonic constraints).
SACAPF: Simultaneous Allocation of Capacitors and APFs.

7. Intellectual Property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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Hamed Rezapour: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Project administration, Supervision, Writing – original draft. **Farid Fathnia:** Validation, Writing – review & editing, Formal analysis. **Mohammad Fiuzy:** Validation, Writing – review & editing, Data curation. **Hamid Falaghi:** Methodology, Project administration, Supervision, Writing – review & editing. **António Mendes Lopes:** Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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No data was used for the research described in the article.

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