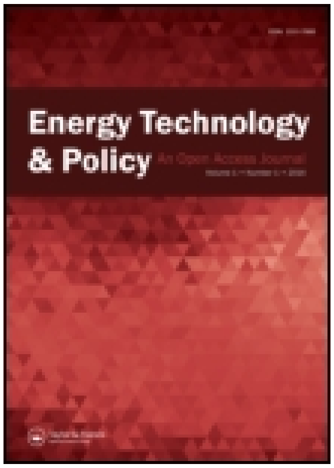

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Islam F. Mohamed[a], Shady H. E. Abdel Aleem[b], Ahmed M. Ibrahim[a] & Ahmed F. Zobaa[c]

[a] Faculty of Engineering, Cairo University, Giza, Cairo, Egypt

[b] 15th of May Higher Institute of Engineering, 15th of May City, Helwan, Cairo, Egypt

[c] School of Engineering and Design, Brunel University, Uxbridge, Middlesex, United Kingdom

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Optimal Sizing of *C*-Type Passive Filters under Non-Sinusoidal Conditions

ISLAM F. MOHAMED[1], SHADY H. E. ABDEL ALEEM[2]*, AHMED M. IBRAHIM[1], and AHMED F. ZOBAA[3]

[1]*Faculty of Engineering, Cairo University, Giza, Cairo, Egypt*
[2]*15th of May Higher Institute of Engineering, 15th of May City, Helwan, Cairo, Egypt*
[3]*School of Engineering and Design, Brunel University, Uxbridge, Middlesex, United Kingdom*

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Abstract: In the literature, much attention has been focused on power system harmonics. One of its important effects is degradation of the load power factor. In this article, a *C*-type filter is used for reducing harmonic distortion, improving system performance, and compensating reactive power in order to improve the load power factor while taking into account economic considerations. Optimal sizing of the *C*-type filter parameters based on maximization of the load power factor as an objective function is determined. The total installation cost of the *C*-type filter and that of the conventional shunt (single-tuned) passive filter are comparatively evaluated. Background voltage and load current harmonics are taken into account. Recommendations defined in IEEE standards 519-1992 and 18-2002 are taken as the main constraints in this study. The presented design is tested using four numerical cases taken from previous publications, and the proposed filter results are compared with those of other published techniques. The results validate that the performance of the *C*-type passive filter as a low-pass filter is acceptable, especially in the case of lower short-circuit capacity systems. The *C*-type filter may achieve the same power factor with a lower total installation cost than a single-tuned passive filter.

Keywords: Harmonic distortion analysis, optimization, passive filters, power quality, power systems harmonics

1. Introduction

Harmonic pollution of electrical distribution systems is not new; it can be found in all industrial facilities. Nonlinear loads seem to be the main source of harmonic pollution in a power distribution system. Degradation of the load power factor, increases in transmission line losses, and reduction of the transmission network efficiency are all expected due to the advance and sophistication of nonlinear loads; the level of voltage harmonic distortion in distribution networks will also increase significantly.[1–8]

There is a set of conventional solutions to the harmonic distortion problems that have existed for a long time. Among these solutions, shunt passive filters are the most frequently employed in power-quality markets because of their low cost, which represents the main interest of most users, in the case of power factor correction and harmonic filtering.[6,9–11] The shunt filters work by short-circuiting harmonic currents as close to the source of distortion as is practical. This keeps the currents out of the supply system.

Practically, the *C*-type filter has been in operation for years. However, a convenient algorithm for sizing its parameters has rarely been discussed in a simple way; when one asks about designing a *C*-type filter or a third-order filter, one discovers the problem. Recently, more researchers have tried to present the basic theory of *C*-type filters and to seek more data about their performance and impact on the power system network within which they are intended to operate.[11] Abdel Aleem et al.[1] introduces an optimal design of the *C*-type passive filter based on minimization of the total harmonic voltage distortion. The *C*-type filter has good suppression at the tuned frequencies and efficiently damps the resonance instead of shifting it to a lower harmonic order; also, it offers lower losses when tuned to low frequencies. However, additional features of the *C*-type filters, especially their installation cost and competitiveness with traditional shunt harmonic passive filters, mainly the single-tuned one, need to be introduced in a simple and convenient manner in order to advance their use in a wide practical domain and to maintain the main advantage of the simplicity of passive filters as a whole.

The optimal design of the passive filters under multi-constraints and multi-objectives is complex since it often involves inconsistent objectives and constraints. It is always

*Address correspondence to: Shady H. E. Abdel Aleem, 15th of May Higher Institute of Engineering, 15th of May City, Helwan, Cairo 11721, Egypt. Email: engyshady@ieee.org

treated as a nonlinear programming problem. Consequently, the Genetic Algorithm toolbox (GA) provided by MatLab software is selected to determine the required optimal design and to establish the suitability and effectiveness of the *C*-type passive filter. GA has several advantages, such as its ability to work with numerical values to build up objective functions without difficulty and its ability to be easily formulated for multi-objective optimization problems for many practical problems.[7,12]

In this article, the optimal design of *C*-type passive filters based on maximization of the power factor when the filter under non-sinusoidal conditions is presented, while taking into account compliance with the following constraints:

- Maintaining the load power factor *PF* in an acceptable specified range ($90\% \leq \mathrm{PF} \leq 100\%$).
- Maintaining the total voltage harmonic distortion *VTHD* at the point of common coupling between the supplier and the customer in an acceptable specified range ($\mathrm{VTHD} \leq 5\%$) with each individual harmonic component being limited to 3%.[13]
- The total current demand distortion (TDD) should be limited to a standard percentage according to the system strength or simply the (I_{SC}/I_L) ratios given in [13].
- Compliance with IEEE Standard 18-2002[14] for shunt power capacitor specifications for its continuous operation.

2. *C*-Type Filter Configuration

The *C*-type filter is included in the category of broadband filters. Generally, broadband filters dampen commutation notches more effectively than single-tuned filters, as they have a much broader bandwidth. Also, they can eliminate inter-harmonics generated by static frequency converters. Besides, they have good ability to dampen the resonance that may occur.[1] Figure 1 illustrates a circuit model of an installed *C*-type filter. In what follows, the equations that express the filter components R_1, L_1, C_1 (main capacitor), and C_2 (auxiliary capacitor) will be investigated. The *C*-type filter has different behaviors with various categories of frequencies and acts as various types of passive filters[1,9] because at fundamental frequency, it acts as a stand-alone capacitor (C_1), where the resistor is bypassed due to the tuned arm (series L_1–C_2); this circuit exhibits much lower losses. As the frequency increases, the filter acts as a single-tuned filter with a damping resistor where the inductor starts to resonate with ($C_1 + C_2$). At higher frequencies, the filter acts as a first-order filter where the inductor magnitude has higher magnitude than the magnitude of ($C_1 + C_2$).

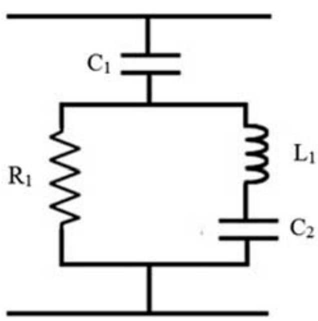

Fig. 1. The configuration of the *C*-type filter.

The impedance of the *C*-type passive filter Z_{Ch} varies with the harmonic order h, where X is the magnitude of the auxiliary capacitive reactance, at fundamental frequency, which is equal to the magnitude of the inductive reactance; it can be illustrated as follows:

$$Z_{Ch} = R_{Fh} + jX_{Fh} = \frac{R * \left[jX\left(h - \frac{1}{h}\right)\right]}{R + \left[jX\left(h - \frac{1}{h}\right)\right]} - j\frac{X_{C1}}{h} \tag{1}$$

where R_{Fh} and X_{Fh} are given as

$$R_{Fh} = \frac{RX_{LCh}^2}{R^2 + X_{LCh}^2} \tag{2}$$

$$X_{Fh} = \frac{R^2 X_{LCh}}{R^2 + X_{LCh}^2} - \frac{X_{C1}}{h} \tag{3}$$

so that

$$X_{LCh} = hX_{L1} - \frac{X_{C2}}{h} = X\left(h - \frac{1}{h}\right) \tag{4}$$

3. System Description

Figure 2 demonstrates a single-phase equivalent circuit of a sample of a distribution system network. It shows the principle of

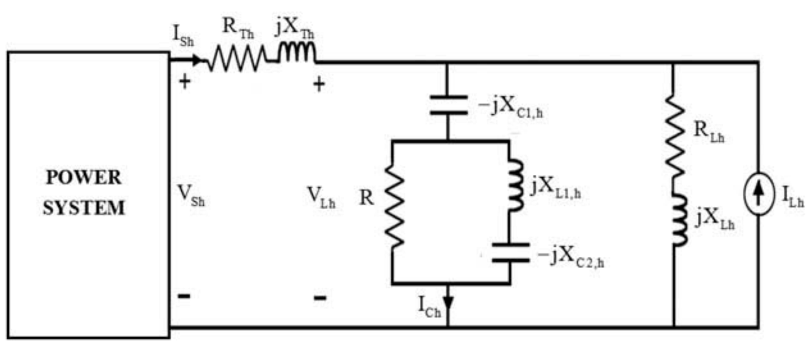

Fig. 2. The system under study.

operation of a *C*-type passive filter dedicated to a harmonic-current-source load (nonlinear load). Also, a background harmonic voltage distortion at harmonic number *h* exists.

Recalling Zobaa et al.,[6] the voltage source representing the utility supply voltage and the harmonic current source representing the nonlinear load are given as functions of time (*t*) as follows:

$$v_S(t) = \sum_h v_{Sh}(t) \quad (5)$$

$$i_L(t) = \sum_h i_{Lh}(t) \quad (6)$$

The *h*th harmonic Thevenin impedance Z_{Th} and load impedance Z_{Lh} are given as

$$Z_{Th} = R_{Th} + jX_{Th} \quad (7)$$

$$Z_{Lh} = R_{Lh} + jX_{Lh} \quad (8)$$

After some derivations using circuit analysis, the *h*th supply current and *h*th compensated load voltage for the system using a *C*-type filter are given, respectively, as

$$I_{Sh} = \frac{NI_{RE} + jNI_{IM}}{D_{RE} + jD_{IM}} \quad (9)$$

$$V_{Lh} = \frac{NV_{RE} + jNV_{IM}}{D_{RE} + jD_{IM}} \quad (10)$$

where

$$NI_{RE} = V_{Sh}(R_{Fh} + R_{Lh}) + I_{Lh}\,(R_{Fh}R_{Lh} - X_{Lh}X_{Fh}) \quad (11)$$

$$NI_{IM} = V_{Sh}\,(X_{Fh} + X_{Lh}) + I_{Lh}\,(R_{Fh}X_{Lh} + R_{Lh}X_{Fh}) \quad (12)$$

$$NV_{RE} = \mu V_{Sh} - I_{Lh}\,((R_{Th}R_{Lh} - X_{Lh}X_{Th})\,R_{Fh} - \alpha X_{Fh}) \quad (13)$$

$$NV_{IM} = \delta V_{Sh} - I_{Lh}\,((R_{Th}R_{Lh} - X_{Lh}X_{Th})\,X_{Fh} + \alpha R_{Fh}) \quad (14)$$

$$D_{RE} = R_{Fh}(R_{Th} + R_{Lh}) - X_{Fh}(X_{Lh} + X_{Th}) + \beta \quad (15)$$

$$D_{IM} = R_{Fh}(X_{Th} + X_{Lh}) + X_{Fh}(R_{Lh} + R_{Th}) + \alpha \quad (16)$$

so that

$$\alpha = (R_{Lh}X_{Th} + R_{Th}X_{Lh})$$

$$\beta = (R_{Th}R_{Lh} - X_{Lh}X_{Th})$$

$$\mu = (R_{Fh}R_{Lh} - X_{Lh}X_{Fh})$$

$$\delta = (R_{Fh}X_{Lh} + R_{Lh}X_{Fh})$$

Hence, the rms values of the compensated load voltage in volts and the compensated supply current in amperes are given as

$$V_L = \sqrt{\sum_{h=1}^{13} V_{Lh}^2} \quad (17)$$

$$I_S = \sqrt{\sum_{h=1}^{13} I_{Sh}^2} \quad (18)$$

For the system under study shown in Figure 2, the main compensated system indices demonstrating the system performance would be given as the following:

The compensated load power factor *PF* is given as

$$PF = \frac{P_L}{V_L I_S} = \frac{\sum_h G_{Lh}V_{Lh}^2}{\sqrt{\sum_h I_{Sh}^2 \sum_h V_{Lh}^2}} \quad (19)$$

Additionally, in terms of fundamental values of the load active and apparent powers, the compensated load displacement power factor *dPF* is given as

$$dPF = \frac{P_{L1}}{V_{L1}I_{S1}} \quad (20)$$

The transmission loss P_{LOSS} is given as

$$P_{LOSS} = \sum_h I_{Sh}^2 R_{Th} \quad (21)$$

Considering the voltage and current harmonics, which are found from (17) and (18), the total voltage harmonic distortion *VTHD* for the load voltage and total current harmonic distortion *ITHD* for the supply current are given as

$$VTHD = \frac{\sqrt{\sum_{h>1} V_{Lh}^2}}{V_{L1}} \quad (22)$$

$$ITHD = \frac{\sqrt{\sum_{h>1} I_{Sh}^2}}{I_{S1}} \quad (23)$$

Finally, the total current demand distortion *TDD* for the supply current based on the maximum demand current, which is chosen to be equal to the rated load current (I_L), is given as

$$TDD = \frac{\sqrt{\sum_{h>1} I_{Sh}^2}}{I_L} \quad (24)$$

The resistances R_{Lh} and R_{Th} are assumed to be frequency-independent (i.e., $R_{Lh} = R_L$ and $R_{Th} = R_T$).[15]

4. Problem Formulation

4.1 Passive Filter Design

The optimal design of the passive filters under multi-constraints and multi-objectives is complex since it often involves inconsistent objectives and constraints. In this article, the optimal design of *C*-type passive filters based on maximization of the power factor under non-sinusoidal conditions and calculation of their installation cost are presented, while taking into account compliance with the following constraints:

- Individual harmonics and total harmonic distortions of the voltage and current measured at the PCC are considered constraints for the proposed optimal design approach due to the harmonic limitations placed in IEEE Standard 519-1992. Accordingly, maintaining the total voltage harmonic distortion *VTHD* and total current demand distortion *TDD* at the PCC between the supplier and the customer in acceptable ranges are the main constraints regarding harmonic suppression with the *C*-type filter.
- Maintaining the load power factor at an acceptable specified range (≥90%) is an important constraint controls amount of the compensated reactive power with the *C*-type filter.
- Compliance with IEEE Standard 18-2002[14] for shunt power capacitor specifications for its continuous operation. To achieve this target, capacitors will be capable of continuous operation provided that none of the following limitations are exceeded[14]:

1. 135% of nominal rms filter current ($I_{nominal}$) based on rated kVA ($S_{nominal}$) and rated voltage ($V_{nominal}$), so that

$$100 * \frac{\sqrt{\sum_h I_{Ch}^2}}{I_{nominal}} \leq 135\% \tag{25}$$

where I_{Ch} is the capacitor current at harmonic number h and is given as

$$I_{Ch} = \frac{[V_{Sh}R_{Lh} - \beta I_{Ln}] + j\,[V_{Sh}X_{Lh} - \alpha I_{Lh}]}{D_{RE} + jD_{IM}} \tag{26}$$

2. 110% of the rated rms voltage, so that

$$100 * \frac{\sqrt{\sum_h V_{Ch}^2}}{V_{nominal}} \leq 110\% \tag{27}$$

where V_{Ch} is the main capacitor voltage at harmonic number h and is given as

$$V_{Ch} = \frac{X_{C1}}{h}\left[\frac{[V_{Sh}R_{Lh} - \beta I_{Lh}] + j\,[V_{Sh}X_{Lh} - \alpha I_{Lh}]}{D_{RE} + jD_{IM}}\right] \tag{28}$$

3. 120% of rated peak voltage ($V_{C,\,Peak}$), so that

$$V_{C,Peak} = \sum_h (I_{Ch})\left(\frac{X_{C1}}{h}\right) \tag{29}$$

4. 135% of nameplate kVA

$$100 * \frac{V_C I_C}{S_{nominal}} \leq 135\% \tag{30}$$

As a result, according to the proposed approach, optimal design problem of the *C*-type passive filter, provided that none of the IEEE Standard 18-2002 limitations are exceeded, can be formulated as follows:

Maximize *PF* (X_{C1}, X, and R)
subjected to:
90% ≤ PF (X_{C1}, X, and R) ≤ 100%,
VTHD (X_{C1}, X, and R) ≤ 5%,
TDD (X_{C1}, X, and R) ≤ Maximum TDD (defined in IEEE 519).

Genetic Algorithm toolbox (GA) provided by MatLab software is selected to determine the required optimal design and to establish the suitability and effectiveness of the *C*-type passive filter. Algorithm is initiated with a set of random solutions named population. An individual solution is represented in an encoded form called chromosome. Each chromosome consists of individual structures called genes. Solutions from one population are used to create a new one.[12] In order to create a new population, GA uses selection procedure. Selection is the procedure of maintaining and ignoring bad solutions from both the current and the next population. In the selection process, the solutions are selected according to their values of objective function (fitness). The more fitness, the more chance of being selected. The algorithms will repeat until a termination condition is satisfied. The best solution is returned to represent the optimum (global) solution.

Real-valued representation of parameters is used because real representations give faster, more consistent, and more accurate results. The goal of genetic algorithms is to search for the *C*-type filter main capacitive reactance (X_{C1}) in order to compensate the system's reactive power, determine the parallel resistance value (R) to ensure the required performance and effectiveness of the proposed filter, and determine reactance value (X) to ensure the required quality of the proposed filter. The optimization fitness (objective function) is based on maximizing load power factor for the system under study with the *C*-type filter, while complying with the IEEE standards 519-1992 and 18-2002 recommendations.

The lower and upper boundaries of the main capacitive reactance (X_{C1}) are selected as the reactance values of a free capacitor that improve the system's actual *dPF* from 71.65 to 100%. The range of variability of the inductive reactance (X) is chosen based on the lower and upper boundaries of the tuning harmonic order which is considered between 2 and 12. This search interval of the tuning harmonic order covers all harmonic orders that are observed in the simulated system. The range of variability of the parallel resistance (R) is chosen between 1 to 100 ohms based on a wide search interval of quality factor of the the *C*-type filter. Population size is chosen to be 100 individuals. Crossover probability equals 0.8. Mutation probability equals 0.01. GA termination condition is 30 generations. Additionally, roulette-wheel selection and shuffling crossover are used in the search algorithm.

4.2 Installation Cost Calculation of the C*-Type Filters*

In most cases, the main objective of a filter is that the values of filter parameters must be optimized to ensure that they are the most well-fitted solution for the specified techno-economic target. The following relations were determined to calculate the total installation cost of the *C*-type passive filters. Richards et al. and Zobaa et al.[16–17] summarize the methods used to calculate the cost of parameters of a conventional shunt (single-tuned) passive harmonic filter. The formulation of the harmonic passive filter cost (COST) is arranged in terms of the filter size that represents the reactive power supplied by the capacitors as follows:

$$\mathrm{COST} = \mathrm{C_{C1}} + \mathrm{C_{C2}} + \mathrm{C_L} + \mathrm{C_E} \tag{31}$$

where C_{C1}, C_{C2}, C_L and C_E are the main capacitor, auxiliary capacitor, reactor, and energy loss costs, respectively. In order to maintain simplicity, the capacitor and inductor costs are assumed to be equal and proportional to their ratings. So the capacitor unit cost in Egyptian pounds per kilovar $W_C = W_L = 50$ L.E./kvar so that

$$\mathrm{C_{C1}} = \mathrm{W_C} * \mathrm{V_{C,Peak}} * \mathrm{I_C} \tag{32}$$

$$\mathrm{C_{C2}} = \mathrm{W_C} * \sqrt{\mathrm{I_{C1}^2} + \sum_{h \succ 1} \mathrm{I_{ah}^2}} * \sum_{h} \left(\mathrm{I_{ah}} \frac{\mathrm{X_{C2}}}{h} \right) \tag{33}$$

$$\mathrm{C_L} = \mathrm{W_L} * \sqrt{\mathrm{I_{C1}^2} + \sum_{h \succ 1} \mathrm{I_{ah}^2}} * \sum_{h} h\mathrm{I_{ah}}\mathrm{X_L} \tag{34}$$

$$\mathrm{C_E} = 8760 * \mathrm{F_V} * \mathrm{U_V} * \frac{(1+\mathrm{T})^{\mathrm{K}} - 1}{\mathrm{T}(1+\mathrm{T})^{\mathrm{K}}} * \sum_{h} \left(\mathrm{I_{Ch}^2} \mathrm{R_{Fh}} \right) \tag{35}$$

It must be mentioned that the constants included in the previous equations are chosen based on the Egyptian tariff. They can be summarized as follows: interest rate $T = 0.05$, filter lifetime $K = 15$ years, filter utilization factor $U_V = 1.0$, and the cost of power loss per kilowatt hour $F_V = 0.20$ L.E./kwhr [17], where I_{ah} is the *h*th auxiliary capacitor current in amperes.

5. Results and Discussion

Four cases of an industrial plant (Table 1) were simulated using the GA optimization method. The numerical data were taken from an example in IEEE Standard 519-1992.[13,18] Two short-circuit capacity expressed in mega volt-amperes system capacities are used in the study cases, where the 80 $\mathrm{MVA_{SC}}$ is used in Cases 1 and 2, representing a weak system, while the 150 $\mathrm{MVA_{SC}}$ is used in Cases 3 and 4, representing a stiff one. The three-phase active-power is 5100 kW and the three-phase inductive reactive-power is 4965 kvar. The 60-cycle supply line voltage is 4160 V. It is assumed that the load harmonics are not sufficiently serious to employ a harmonic filter, but when combined with source harmonics the usage of a pure capacitor would degrade the power factor and overload equipment. Consequently, a *C*-type passive filter is selected.[19]

Table 2 shows the uncompensated system results to be defined and compared with the proposed filter results. Table 3 shows a summary of the results for the four case studies. Table 4 shows the expected installation cost of the *C*-type filter parameters. Comparison of the simulated results given in Tables 2 and 3 shows that the general performance of the method is satisfactory, providing improvement of the system's overall performance. Additionally, Table 3 shows that the proposed technique results in reduction of the supply current, lower transmission loss, higher transmission efficiency, and higher load power factor compared to the uncompensated system results shown in Table 2.

Table 1. Four cases of an industrial plant under study and their simulation results.

Parameters	Case 1	Case 2	Case 3	Case 4
Short-circuit capacity (MVA)	80		150	
V_{S1} (kV)	2.40	2.40	2.40	2.40
R_{T1} (Ω)	0.02163	0.02163	0.01154	0.01154
X_{T1} (Ω)	0.2163	0.2163	0.1154	0.1154
R_{L1} (Ω)	1.7421	1.7421	1.7421	1.7421
X_{L1} (Ω)	1.696	1.696	1.696	1.696
V_{S5} (V)	72	96	72	96
V_{S7} (V)	48	72	48	72
V_{S11} (V)	24	48	24	48
V_{S13} (V)	12	24	12	24
I_{L5} (A)	33	33	33	33
I_{L7} (A)	25	25	25	25
I_{L11} (A)	9	9	9	9
I_{L13} (A)	8	8	8	8

Table 2. Simulated results of the uncompensated system.

Parameters and cases	Case 1	Case 2	Case 3	Case 4
PF (%)	71.53	71.48	71.53	71.49
dPF (%)	71.65	71.65	71.65	71.65
I_S (A)	923.42	923.47	952.87	952.93
V_L(V)	2245.07	2246.59	2316.19	2317.83
P_{Loss} (kW)	18.45	18.45	10.48	10.48
VTHD (%)	3.71	4.48	3.19	4.09
ITHD (%)	4.35	4.45	4.45	4.55
TDD (%)	4.02	4.11	4.24	4.33

Table 3. Simulated results in the four cases for the optimization process for the *C*-type filter.

Parameters and cases	Case 1	Case 2	Case 3	Case 4
X_{C1} (Ω)	3.485	3.483	3.484	3.481
X (Ω)	0.668	0.788	0.801	0.498
R (Ω)	93.839	89.093	88.090	79.071
PF (%)	99.800	99.720	99.750	99.520
dPF (%)	99.990	99.990	99.990	99.990
I_S (A)	702.520	702.890	705.970	707.370
V_L(V)	2381.100	2382.150	2391.760	2392.560
P_{Loss} (kW)	10.680	10.690	5.750	5.770
VTHD (%)	2.560	3.240	2.640	3.010
ITHD (%)	5.410	6.070	6.280	8.340
TDD (%)	3.800	4.260	4.420	5.870

Table 4. Cost of the *C*-type filter parameters.

Parameters and cases	Case 1	Case 2	Case 3	Case 4
C_{C1} (thousands of L.E.)	82.104	82.253	83.751	82.7350
C_{C2} (thousands of L.E.)	15.738	18.609	11.981	18.9970
C_L (thousands of L.E.)	21.819	26.683	20.080	24.9580
C_E (thousands of L.E.)	1.450	2.545	3.545	1.6366
COST (thousands of L.E.)	121.049	130.159	119.367	128.3480

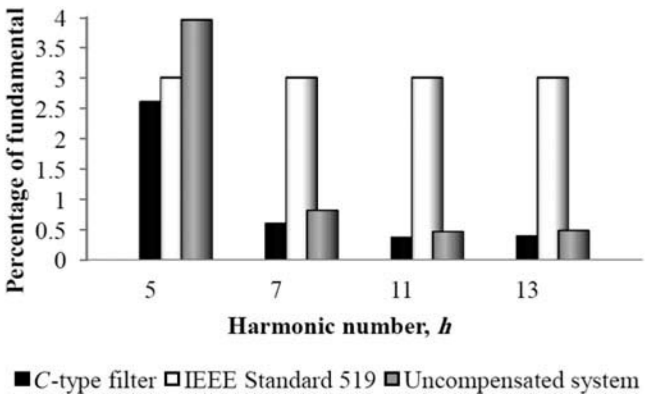

Fig. 3. Harmonic content of the load voltage, Case 2.

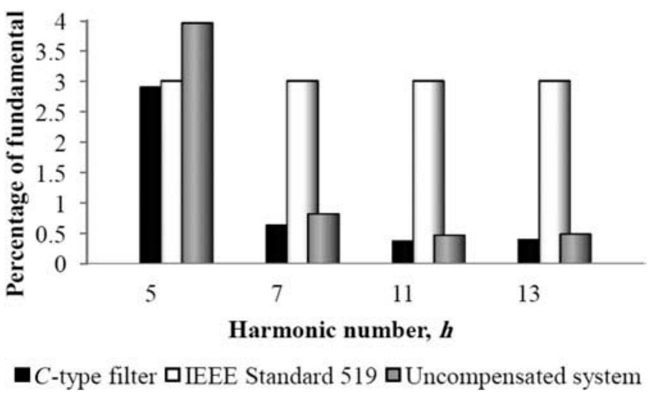

Fig. 4. Harmonic content of the load voltage, Case 4.

As shown in Table 3, the *VTHD* is dramatically reduced, satisfying the main concern of the IEEE standard 519. Figures 3 and 4 show the values of the load harmonic voltage after compensation where the proposed filter is introduced compared with values for the uncompensated system and the IEEE 519 limits.

Figure 5 shows the harmonic content of the supply current, before and after compensation, for the lower short-circuit capacity system (Case 1), while Figure 6 shows the harmonic content of the supply current, before and after compensation, for the higher short-circuit capacity system (Case 3), both with the same input data for harmonic contents. It has been shown that under distorted supply voltages, any trial to increase the power factor results in an increase in the *ITHD*.[6,18] However, the individual harmonic supply currents and the *TDD* percentage meet the standard limits defined in IEEE 519.

Table 5 shows the calculated capacitor limits for all cases. Comparison of the calculated and standard limits shows that all values lie within the standard limits in the optimal filter design for all studied cases.

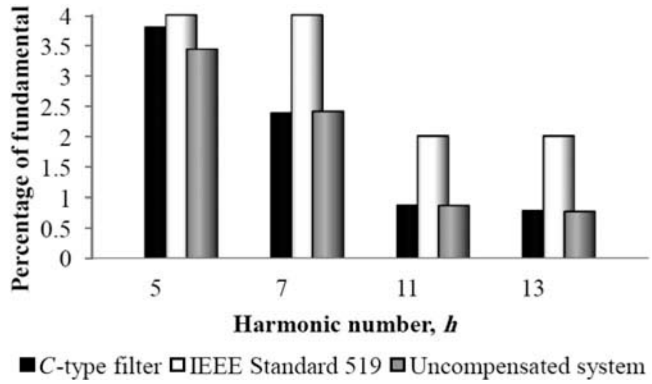

Fig. 5. Harmonic content of the supply current, Case 1.

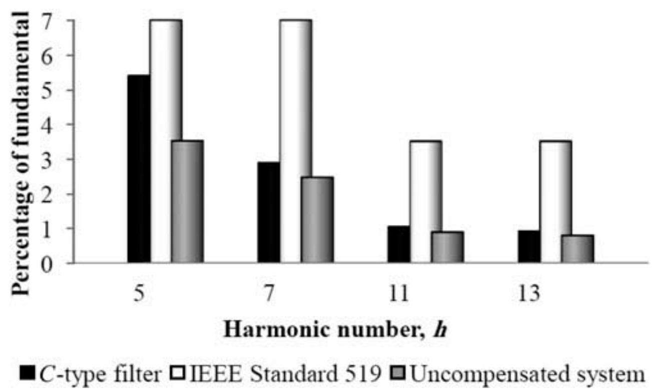

Fig. 6. Harmonic content of the supply current, Case 3.

Table 5. Capacitor loading duties.

Parameters	Case 1	Case 2	Case 3	Case 4
Rms voltage (%)	99.17	99.17	99.61	99.62
Peak voltage (%)	100.13	100.24	100.44	101.40
Rms current (%)	99.22	99.24	99.65	99.83
Apparent power (%)	99.35	99.48	100.09	101.23

Table 6. Comparison of calculated and simulated *VTHD* and *ITHD* percentages.

Parameters and cases	Frequency-domain analysis		Time-domain analysis	
	VTHD (%)	*ITHD* (%)	*VTHD* (%)	*ITHD* (%)
Case 1	2.56	5.41	2.56	5.26
Case 2	3.24	6.07	3.26	6.33
Case 3	2.64	6.28	2.62	6.34
Case 4	3.01	8.34	3.15	8.10

The numerical results for the system under study with time-domain simulation are presented based on Simulink of MatLab software. Table 6 shows the total harmonic distortion percentages for the load voltage and the supply current measured at the point of common coupling based on both frequency and time-domain simulations, respectively. It is obvious the reasonable agreement between them.

Figures 7 and 8 show the linear impedance-frequency scan for the system under study: Cases 2 and 4, respectively, both seen from the harmonic-source side.[17] It is obvious from both figures that *C*-type filters are more durable to parallel resonance hazards, especially in the case of lower short-circuit capacity systems.[1]

For equal short-circuit capacity systems, the additional supply voltage harmonic contents for the same harmonic load will result in an increase in the line current passing through the compensated load and thus a decrease in the load power factor.[20] Also, an increase in the voltage and current total harmonic distortions will be obvious. The transmission efficiency decreases because of the higher transmission losses and thus higher transmission voltage drop. Furthermore, the compensator components rating increases, which will be reflected in their cost.[21]

Considering the total installation costs of the *C*-type filter and the conventional single-tuned passive filter presented in Abdel-Aziz et al.,[15] Figures 9 and 10 show installation cost

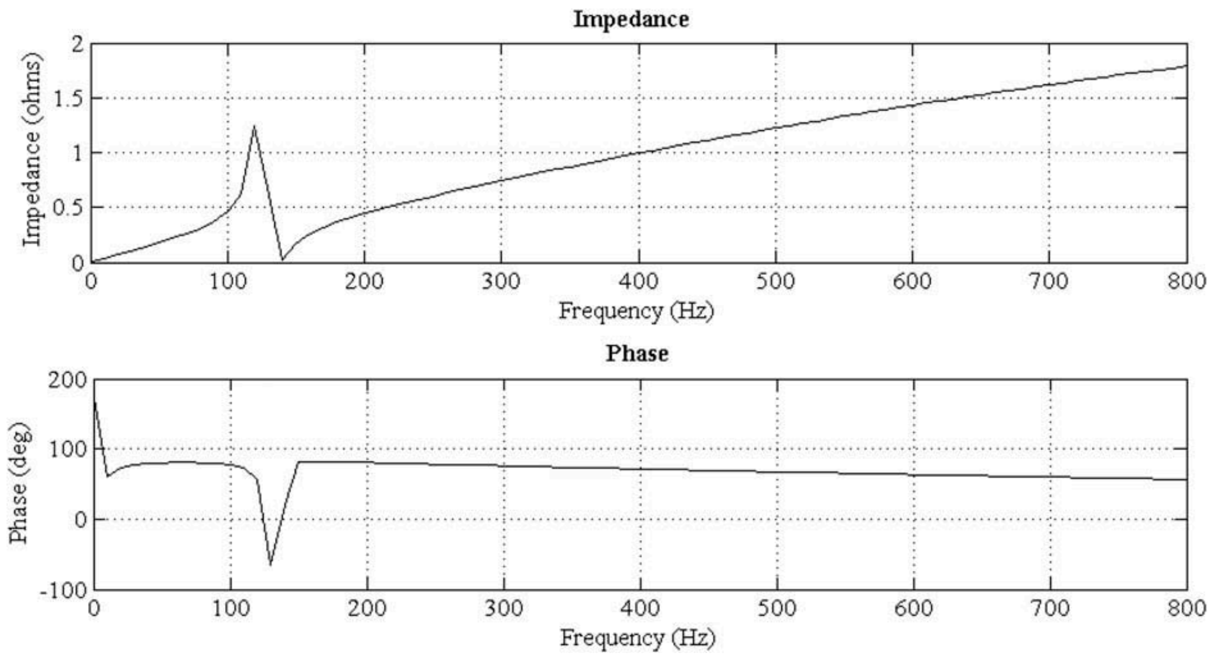

Fig. 7. Linear impedance-frequency scan, Case 2.

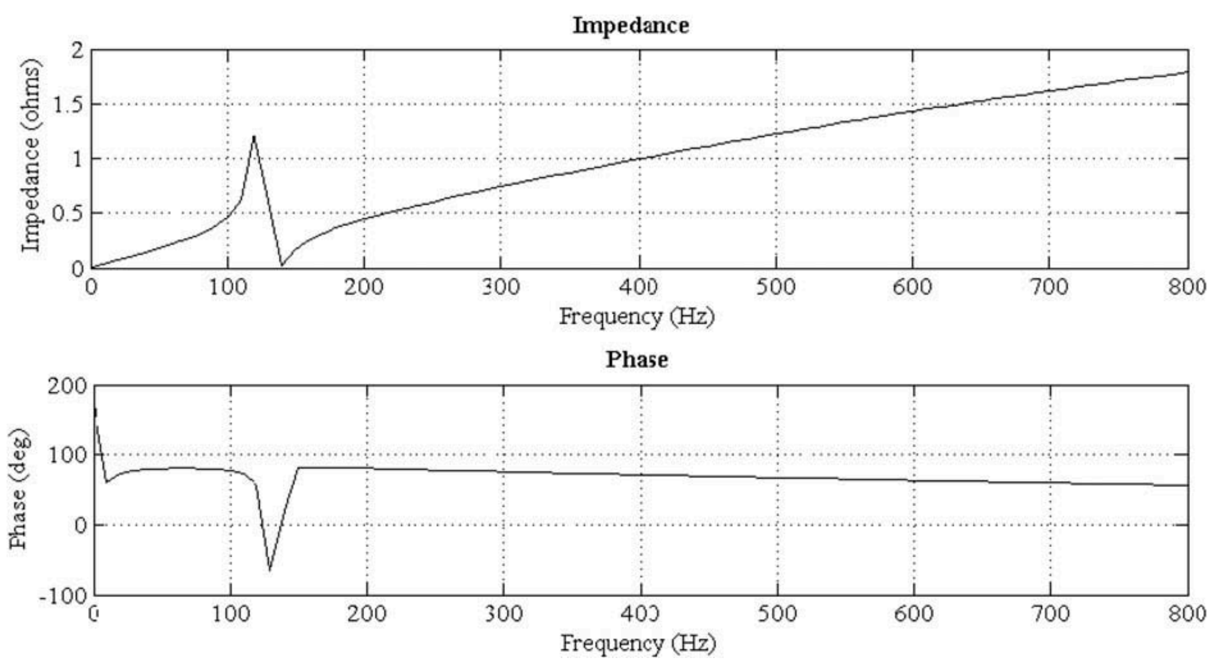

Fig. 8. Linear impedance-frequency scan, Case 4.

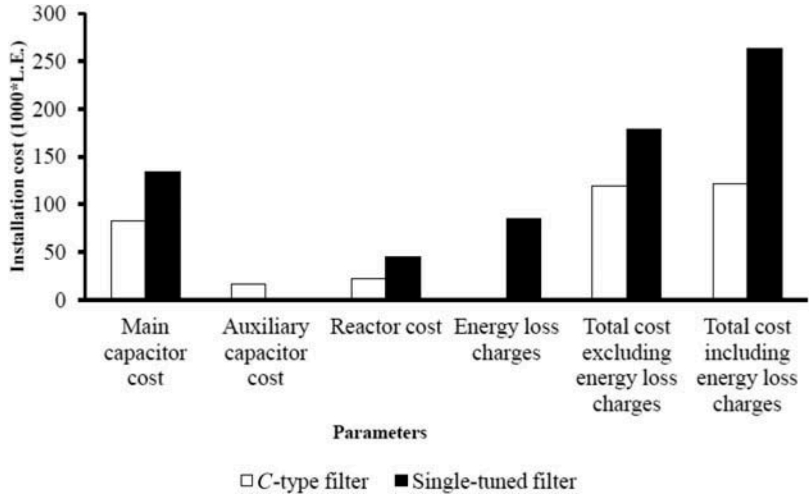

Fig. 9. Cost comparison of *C*-type and single-tuned passive filters, Case 1.

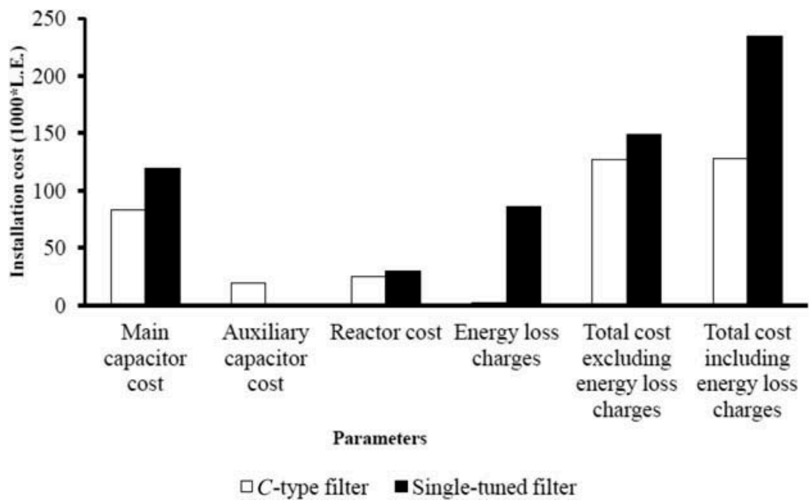

Fig. 10. Cost comparison of *C*-type and single-tuned passive filters, Case 3.

comparison between the two filters for the system under study in Cases 1 and 3, respectively. The conventional single-tuned passive filter data are taken from Zobaa et al.[6] and Abdel-Aziz et al.[15] However, it must be mentioned that the equivalent resistance of the reactor at fundamental frequency was ignored in Zobaa et al.[6] and Abdel-Aziz et al.[15]; thus, in the comparison it is assumed to have the smallest acceptable value of 1% of the fundamental value of the compensator reactor. This allows it to be taken into account in the results rather than being neglected. Additionally, Table 7 presents a comparison of the present method and the method presented in Abdel-Aziz et al.,[15] for all cases under study. It is obvious that results of the proposed filter are similar to those presented in Abdel-Aziz et al.[15]

Tables 3 and 7 show that the proposed filter provides higher *PF* percentage when compared to the conventional filter. It can also be observed that I_S, V_L, and *dPF* values obtained by the proposed filter and the conventional filter presented in Abdel-Aziz et al.[15] are very close to each other. Finally, it can be mentioned that the proposed filter has lower *VTHD, ITHD,* and P_{LOSS} values than those presented in Abdel-Aziz et al.[15]

Table 7. Simulated results in the four cases for the optimization process for the single-tuned passive filter presented in Abdel-Aziz.[15]

Parameters and cases	Case 1	Case 2	Case 3	Case 4
X_{C1} (Ω)	4.73	4.73	4.15	4.15
X (Ω)	1.25	1.25	0.66	0.66
R (Ω)	0.012	0.012	0.006	0.006
PF (%)	99.67	99.59	99.50	99.37
dPF (%)	100	100	100	100
I_S (A)	702.93	703.11	707.32	707.8
V_L(V)	2383.44	2384.84	2393.59	2395.06
P_{Loss} (kW)	10.64	10.64	5.74	5.74
VTHD (%)	6.59	7.82	6.24	7.55
ITHD (%)	6.54	6.93	8.93	9.66
COST (thousands of L.E.)	178	181	149	151.5

Additionally, it is obvious that the installation cost of the *C*-type passive filter is reasonable compared to the single-tuned passive filter, which gives the proposed filter a great advantage as a reasonably competitive cost solution. It is also evident that the *C*-type passive filter is cheaper than the conventional shunt filter when the energy loss cost is included because of its lower power loss.

In conventional harmonic filtering methods, single-tuned and high-pass filters are employed to suppress harmonic currents injected in the power system. Single-tuned filters provide strong reduction of harmonic currents at a specific tuning harmonic number but suffer from series and parallel resonance. High-pass filters attenuate high-order harmonic currents; however, they cannot be tuned to a lower-order harmonic due to their expected large power losses and installation cost. In this article, the *C*-type filter is employed as a different approach in low-pass filtering to avoid the previous disadvantages of conventional shunt passive filters.[1] It is obvious that the *C*-type passive filter can work effectively as a low-pass filter and mitigates low-order harmonics with a good harmonic attenuation at its tuned frequency, especially in the case of lower short-circuit capacity systems compared to systems with higher short-circuit capacity. Besides, the *C*-type filter promises low ohmic losses compared to the conventional low-pass and high-pass passive filter configurations. Finally, the *C*-type filter may achieve the same power factor with a lower total installation cost than a single-tuned passive filter.

6. Conclusions

For nonlinear loads, it is necessary to use harmonic filters. Such filters have dual purposes: the first is to improve the associated poor power factor, and the second is to prevent the harmonic load currents from being injected into the network. In this article, the general system performance when using *C*-type filters as low-pass filters is implemented and discussed. Four cases with two different system short-circuit capacities have been tested, and the general performance of the method used is satisfactory, providing improvement of distortion levels and power factor correction compared with other published results. The required investment cost is estimated for the *C*-type passive filter, and it was evident that the *C*-type filter may achieve the same load power factor with a lower installation cost than a conventional single-tuned passive filter.

Appendix: Nomenclature

C_1:	Main capacitor of the *C*-type filter in microfarads
C_2:	Auxiliary capacitor of the *C*-type filter in microfarads
C_{C1}:	Main capacitor cost of the *C*-type filter in Egyptian pounds
C_{C2}:	Auxiliary capacitor cost of the *C*-type filter in Egyptian pounds
C_E:	The present value cost of energy losses in Egyptian pounds
C_L:	Reactor cost of the *C*-type filter in Egyptian pounds
COST:	Total *C*-type filter installation cost in Egyptian pounds
dPF:	Displacement power factor as a percentage
F_V:	Filter utilization factor
G_{Lh}:	Load conductance at harmonic number *h* in mhos
H	Harmonic number
I_{ah}:	Auxiliary capacitor current at harmonic number *h* in amperes
I_{Ch}:	Main capacitor current at harmonic number *h* in amperes
I_C:	Rms value of the main capacitor current in amperes
I_L:	Rms value of the rated load current in amperes
I_{Lh}:	Load current in amperes at harmonic number *h*
I_S:	Root-mean-square (rms) value of supply current in amperes
I_{SC}:	Rms value of the short-circuit current in amperes
I_{Sh}:	Supply current in amperes at harmonic number *h*
ITHD:	Current total harmonic distortion as a percentage
K:	Filter lifetime in years
L_1:	Inductance of the *C*-type filter in henrys
PF:	Load power factor as a percentage
P_L:	Load active power per phase in watts
P_{Loss}:	Transmission power loss in watts
P_S:	Supply active power per phase in watts
Q_C:	Main capacitor rating in reactive volt-amperes
R_1:	Damping resistor of the *C*-type filter in ohms
R_F, X_F:	Fundamental values of the equivalent resistance and reactance of the *C*-type filter in ohms
R_{Fh}, X_{Fh}:	*C*-type filter resistance and reactance in ohms at harmonic number *h*
R_{Lh}, X_{Lh}:	Load resistance and reactance in ohms at harmonic number *h*
R_{Th}, X_{Th}:	Thevenin source resistance and reactance in ohms at harmonic number *h*
TDD:	Total demand distortion as a percentage
U_V:	Cost of power loss in Egyptian pounds per kilowatt hours
V_C:	Rms value of the main capacitor voltage in volts
V_{Ch}:	The main capacitor voltage at harmonic number *h* in volts
V_L:	Rms value of load voltage (line to neutral) in volts
V_{Lh}:	Load voltage in volts at harmonic number *h*
V_S:	Rms value of supply voltage (line to neutral) in volts
V_{Sh}:	Supply voltage at harmonic number *h* in volts
VTHD:	Voltage total harmonic distortion as a percentage
W_C, W_L:	Capacitor and reactor unit costs in Egyptian pounds per kilovar
X:	Magnitude of the auxiliary capacitive reactance or the inductive reactance of the *C*-type filter at fundamental frequency in ohms
X_{C1}:	Magnitude of the main capacitive reactance of the *C*-type filter at fundamental frequency in ohms
Z_{Ch}:	The *h*th harmonics impedance of the *C*-type filter in ohms
Z_{Lh}:	The *h*th harmonics load impedance in ohms
Z_{Th}:	The *h*th harmonics transmission impedance in ohms

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