A New Approach for Harmonic Distortion Minimization in Power Systems Supplying Nonlinear Loads

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Abstract— In view of the many problems associated with harmonics pollution within industrial firms, the development of new passive and/or hybrid filtering techniques of higher quality, higher efficiency, and lower cost is a necessity for the forthcoming power quality age. This article suggests a hybrid passive filter, which consists of a certain combination of a shunt passive filter with a series passive portion, as a substitute to overcome the shortcomings of conventional shunt passive filtering techniques. Constrained optimization is used to find the optimal sizing of parameters of the hybrid passive filter in order to reduce both harmonic voltages and harmonic currents in the power system to an acceptable level, as well as to improve the load power factor. The optimal design of the hybrid passive filter and its feasibility are compared to those of the *C*-type passive filter and the conventional shunt passive filter by means of four study cases taken from existing publications. Several simulation results are shown in order to highlight the viability of the proposed filter.

Index Terms— Power systems harmonics, passive filters, power quality, harmonic distortions.

I. INTRODUCTION

The use of passive filters is preferred because of their simplicity, flexibility and economical cost. They are commonly classified according to harmonic suppression techniques into shunt and series passive filters. Series passive filters are given by parallel inductance and capacitance and are resonated at a specific harmonic order to put forward a high blocking impedance, and it is known that these kinds of filters must withstand the rated load current. Therefore they can generate notable losses and voltage drops at the fundamental frequency. Given the prominent cost of the series passive filters as well as their disadvantages, the actual technical and economical approach to current harmonics suppression is to use shunt passive filters (*SPFs*) [1]–[4].

SPFs present very a low impedance path at the resonant frequency and divert most of the harmonic current at that frequency; however, the risk in passive filters' practical manipulation is still very serious, because of their dependence on the source impedance, which is not determined accurately, in addition to the possibility of occurrence of series and/or parallel resonance and distortion in the voltage at the point of common coupling (PCC). Recently, as well as the conventional shunt passive techniques, the *C*-type passive filter (*CPF*) has been proposed, which has a good suppression at the tuned frequencies and does not result in a parallel resonance. Also, it is appropriate for randomly varying loads [5]–[8]. Unfortunately, it was clear from real practice that using *SPFs* or the recent *CPFs* improves the quality of voltage but cannot meet the requirements of the current harmonic component reduction. Consequently, in the last years, topologies combining different configurations of fixed passive and/or adaptive passive facilities have been developed. Recently, [3] introduced an adaptive hybrid system configuration, which consists of a series passive filter, a shunt passive filter, and a thyristor-controlled reactor (TCR), in order to solve the problems caused by using stand-alone passive filters, and removing the resonance that may occur, especially for variable-load reactive-power demand. Despite the valuable development added by such a hybrid filter, the most managed solution for power factor correction and harmonic compensation is still the fixed passive facility, mainly in the standing industrial firms.

In this paper, a suggested fixed hybrid passive filter is investigated as a combination between series and shunt passive topologies to minimize both harmonic voltages and currents in the power system to an acceptable level at the *PCC*, regardless of the source impedance, and also to improve the load power factor to a desired value ($\geq$ 90%). The technical and economic merits of the proposed hybrid passive filter (HPF) compared to the *CPF* presented in [6] and the *SPF* presented in [1] are discussed by means of different study cases.

The well-known optimization technique *FFSQP* (A FORTRAN code for solving optimization problems, possibly minimax, with general inequality constraints and linear equality constraints, generating feasible iterates) is used for the filter constrained optimal design. Recently, [6] examined the effect of this search code on the performance of the *CPF*, and the general search formulation was attractive, owing to the basic principle of sequential approximation in replacing the

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given nonlinear problem with a sequence of subproblems that are easier to solve. The quadratic programming subproblems are always consistent, i.e., a feasible solution always exists, and the objective function may be used directly as a merit function in the line search. Readers should refer to [6] and [9] for the exact formulations of the search algorithm using the *FFSQP* package.

II. HYBRID PASSIVE FILTER TOPOLOGY

Fig. 1 demonstrates a circuit model of the proposed *HPF*. The main feature of the *HPF* which differs from other passive features is its series components L_{SE} and C_{SE}, which resonate at the fundamental frequency, and thus the fundamental current is permitted to pass freely under the influence of the shunt portion only. In other words, the series capacitor is sized so that the magnitude of its capacitive reactance is equal to the magnitude of the series inductive reactance at the fundamental frequency equals X_{SE}. Thus the filter acts as a conventional single tuned filter at the fundamental frequency with a small, additional, voltage drop in the series portion due to the not null resistance R_{SE} of the series inductor. In practice, the internal resistance of a compensator reactor varies in the range of 1% up to 5% with respect to the magnitude of its fundamental reactance [10]. Actually, power dissipation in the compensator reactor, however small, will take place. As the frequency increases, the inductor L_{SH} starts to resonate with C_{SH} at a certain resonant frequency, which makes the filter act as a single-tuned filter with a blocking reactor. This series reactor provides adequate blocking impedance to reduce any current harmonics already presented. Accordingly, the shunt filter capacitor does not become overloaded. The series reactor also acts as an isolator between the power system and the drive and also isolates the possible influences of the line harmonic voltages on the load and filter. It prevents the parallel and the series resonance with the utility and/or other loads at the harmonic frequencies, (it moves the filter parallel resonance frequency away from prevailing current harmonics caused by nonlinear load). Therefore, there is no harmonic amplification, and, promisingly, it has a better current quality than other fixed passive filtering methods.
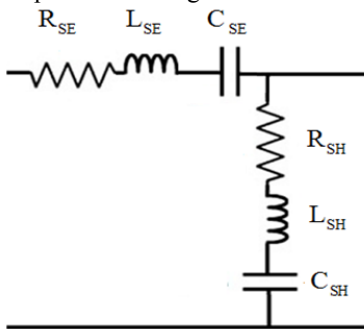

Fig.1. Proposed *HPF* equivalent circuit

The design of the *HPF* has been carried out in two stages: the design of the shunt branch impedance Z_{Hk} at the *k*th harmonic order and the design of the series branch impedance Z_{Ek} at the *k*th harmonic order forming a high blocking filter, as follows:

$$Z_{Hk} = R_{SH} + j(kX_{LSH} - \frac{X_{CSH}}{k}) \tag{1}$$

$$Z_{Ek} = R_{SE} + j(kX_{LSE} - \frac{X_{CSE}}{k}) = R_{SE} + jX_{SE}(k - \frac{1}{k}) \tag{2}$$

The magnitude of the fundamental capacitive reactance of the shunt portion X_{CSH} can be easily calculated if the fundamental reactive power supplied by the shunt portion capacitance Q_{C1} is known, also the magnitude of the inductive reactance of the shunt portion X_{LSH} is related to X_{CSH} by the shunt tuned harmonic order, k^*, as follows:

$$X_{CSH} = \frac{k^2}{k^2 - 1}\left(\frac{V_{L1}^2}{n * Q_{L1}}\right) = \frac{k^2}{k^2 - 1}\left(\frac{V_{L1}^2}{Q_{C1}}\right) \tag{3}$$

$$X_{LSH} = \frac{X_{CSH}}{\left(k^*\right)^2} \tag{4}$$

where: V_{L1} is the fundamental voltage at the shunt portion's bus. Q_{L1} is the fundamental reactive power demanded by the load and *n* is a factor that allows incremental discrete steps of Q_{C1}. It is commonly suggested in low voltage industrial applications that the step of Q_{C1} is 50 *kvar* [11]. Also, the shunt capacitor's nominal voltage is assumed to be equal to the fundamental source voltage V_{S1} to avoid the capacitor loading [10].

For the series portion design, it must be sized to carry the full feeder load; it must consume low reactive power and withstands the nominal system current I_S. At the same time, the series inductance L_{SE} should be relatively large to enhance the current quality. Thus, the following have to be met:

1. At k=1; $X_{LSE} = X_{CSE} = X_{SE,}$
2. R_{SE} equals 1% with respect to X_{SE} in order to maintain the additional voltage drop and joule losses as small as possible.
3. $|X_{SE}|$ is given in Equation (5); *m* is an incremental factor varying with step of 0.01, so that the reactive power consumed by the series portion is less than or equal 25% with respect to the fundamental reactive power demanded by the load [12], [13].

$$\left|X_{SE}\right| = m\frac{Q_{L1}}{I_S^2} \tag{5}$$

4. The series capacitor has been used for tuning the series reactor at the fundamental frequency, in order to minimize the fundamental voltage drop. From the harmonics point of view, it has noticeable effect on the frequency response at very low frequencies (sub-harmonics), but little or no effects at higher frequencies.

The shunt filter impedance equals R_{SH} at the resonant frequency. Recalling the method presented in [6], the shunt resistance is designed by determination of the maximum percentage fraction of the current (I_{SPU}) that is allowed to flow through the supply reactance and the blocking series portion, at the shunt tuned harmonic order, k^*. Therefore,

$$R_{SH}(k^*) = \frac{\left(k^* X_T + X_{SE}\left(k^* - \frac{1}{k^*}\right)\right)}{\sqrt{\left(\frac{1}{I_{SPU}(k^*)}\right)^2 - 1}} \quad (6)$$

The relationship among R_{SH}, quality factor (q), and bandwidth (B_P) are:

$$q = \frac{k^* X_{LSH}}{R_{SH}}, \text{and } B_P = \frac{k^* f_1}{q} \quad (7)$$

where f_1 is the fundamental frequency in Hz.

III. COMPENSATED SYSTEM CONFIGURATION AND HARMONIC RESONANCE CONSTRAINTS

Fig. 2 shows the single phase equivalent circuit of the system configuration under study, where R_L and X_L are the magnitudes of load resistance and reactance, respectively, also, R_T and X_T are the magnitudes of the source resistance and reactance, all expressed in ohms at the fundamental frequency. The kth harmonic Thevenin source impedance and the kth harmonic load impedance are given as

$$Z_{Tk} = R_T + jkX_T \quad (8)$$
$$Z_{Lk} = R_L + jkX_L \quad (9)$$

Voltage source nonlinearity is represented in the source harmonic voltages as V_{Sk}. Also, load nonlinearity is represented in harmonic load currents as I_{Lk} [6]. In order to maintain simplicity; the constant current source model is used for the representation of the nonlinear load. This model is usually placed in the analysis focused on resonance. According to [14], the constant current source model is adequate for the representation of the nonlinear loads under the non-sinusoidal voltage with total harmonic distortion on order of 10%. I_{Sk} is the supply current at the kth harmonic order, it is given as
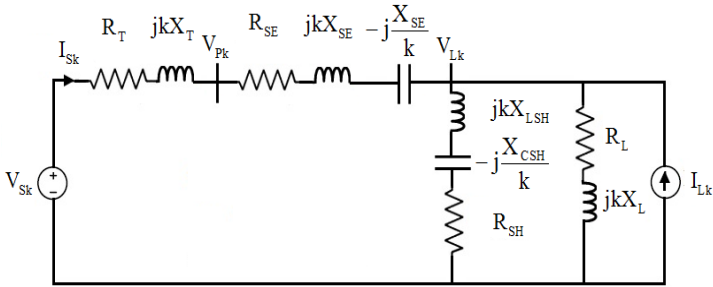

Fig.2. Configuration of the system under study

$$I_{Sk} = \frac{[M_1] + j[M_2]}{[P_1] + j[P_2]} \quad (10)$$

Also, the load voltage V_{Lk} and the compensated *PCC* voltage V_{Pk} at the kth harmonic order are given as:

$$V_{Lk} = \frac{[N_1] + j[N_2]}{[P_1] + j[P_2]} \quad (11)$$

$$V_{Pk} = \frac{[Q_1] + j[Q_2]}{[P_1] + j[P_2]} \quad (12)$$

where

$$M_1 = V_{Sk}(R_{SH} + R_L) + I_{Lk} C_3,$$
$$M_2 = V_{Sk}(C_5 + kX_L) + I_{Lk} C_4,$$
$$N_1 = V_{Sk} C_3 - I_{Lk}(C_1 R_{SH} - C_2 C_5 - C_4 C_6),$$
$$N_2 = V_{Sk} C_4 - I_{Lk}(C_1 C_5 + C_2 R_{SH} + C_3 C_6),$$
$$Q_1 = V_{Sk}(C_3 - C_6(C_5 + kX_L)) - I_{Lk}(C_1 R_{SH} - C_2 C_5),$$
$$Q_2 = V_{Sk}(C_4 + C_6(R_{SH} + R_L)) - I_{Lk}(C_1 C_5 + C_2 R_{SH}),$$
$$P_1 = (C_1 + R_{SH}(R_T + R_L)) - (C_5 X_{TL}) - (C_6(C_5 + kX_L)),$$
$$P_2 = (C_2 + R_{SH} X_{TL}) + (C_5(R_T + R_L)) + (C_6(R_L + R_{SH}))$$
$$C_1 = R_T R_L - k^2 X_T X_L, \quad C_2 = R_T kX_L + R_L kX_T,$$
$$C_3 = R_{SH} R_L - C_5 kX_L, C_4 = R_{SH} kX_L + C_5 R_L,$$
$$C_5 = kX_{LSH} - \frac{X_{CSH}}{k}, C_6 = X_{SE}\left(k - \frac{1}{k}\right), X_{TL} = k(X_T + X_L).$$

The resonance countermeasure is an important factor in harmonic passive filters design. Resonance values can be derived as shown below [15], [16].

A. Voltage resonance (series resonance) condition

For the system under study shown in Fig. 2, the kth source side Thevenin impedance is given as,

$$Z_k = Z_{Tk} + Z_{Ek} + (Z_{Lk} // Z_{Hk}) \quad (13)$$

where $//$ means "in parallel with". Setting its imaginary component equals to zero, simplifying, and considering the load resistance and/or reactance large enough [10]; the voltage resonance equation can be approximated as:

$$\left(kX_T + X_{SE}\left(k - \frac{1}{k}\right)\right) + (kX_{LSH}) - \frac{X_{CSH}}{k} = 0 \quad (14)$$

This represents the resonance between combination of the source impedance and the series portion impedance with the shunt compensator.

B. Current resonance (Parallel resonance) condition

As the total susceptance (B_k) of the proposed compensator with the system circuit at harmonic order k becomes zero, parallel current resonance can be occurred, B_k is given as

$$B_k = \frac{(X_{SE}/k) - k(X_T + X_{SE})}{(R_T^2 + R_{SE}^2) + (k(X_T + X_{SE}) - (X_{SE}/k))^2}$$
$$- \frac{kX_L}{R_L^2 + k^2 X_L^2} - \frac{kX_{LSH} - X_{CSH}/k}{R_{SH}^2 + (kX_{LSH} - X_{CSH}/k)^2} \quad (15)$$

Thus a current resonance constraint is recognized so that ($B_k \geq 0$) at any adjacent harmonic order. Simplifying and solving (15); unwanted current resonant harmonic orders can be passed over [2].

IV. COST ESTIMATION

Ref. [10] describes the method for the evaluation of the parameters of the conventional shunt compensator for nonlinear loads, taking into account cost constraints. Thus, the total cost of the *HPF* (TCOST) can be calculated as follows:

$$TCOST = C_C + C_L + S_C + S_L \quad (16)$$

so that

$$C_C = U_C * \left[I_{Ck}^2 \right]^{1/2} * \left[\sum_k I_{Ck} \frac{X_{CSH}}{k} \right] \qquad (17)$$

$$C_L = U_L * \left[I_{Ck}^2 \right]^{1/2} * \left[\sum_k I_{Ck} k X_{LSH} \right] \qquad (18)$$

$$S_C = U_C * \left[I_{Sk}^2 \right]^{1/2} * \left[\sum_k I_{Sk} \frac{X_{CSH}}{k} \right] \qquad (19)$$

$$S_L = U_L * \left[I_{Sk}^2 \right]^{1/2} * \left[\sum_k I_{Sk} k X_{LSH} \right] \qquad (20)$$

The harmonic voltages are added linearly in Equations (17) - (20) in the first summation to emphasize the effect of the resultant peak (as opposed to rms) voltage on compensator cost [17], where (C_C, C_L) are the shunt capacitor and reactor costs and (S_C, S_L) are the series capacitor and reactor costs, all expressed in dollars. Also, I_{Ck} is the shunt capacitor current at harmonic order k, and is given as

$$I_{Ck} = \frac{V_{Lk}}{Z_{Hk}} \qquad (21)$$

where U_C and U_L are the unit costs of the capacitor and the reactor respectively, and are considered to be constant parameters. In order to maintain simplicity, it is assumed that the unit costs of the capacitors and the reactors are equal, so that, $U_C = U_L = U$ \$/kvar [18].

V. FORMULATION OF THE OBJECTIVE OPTIMIZATION

In typical practical power systems, current distortion is much higher than voltage distortion. This mirrors the basic concern of IEEE 519–1992 [19], in which the higher total harmonic current distortion *ITHD* reflects the total harmonic voltage distortion *VTHD*, leading to its increment at the *PCC*. However, according to the method adopted [20], the most accurate harmonic pollution formula (H.P) can be defined as:

$$H.P = \sqrt{VTHD^2 + ITHD^2 + (VTHD * ITHD)^2} \qquad (22)$$

The fitness of power harmonic filters for both harmonic currents and voltages can be evaluated from such a measurement. Besides, the harmonic resonant constraint, other additional constraints can be summarized as follows:

- According to IEEE 519–1992 [19], *VTHD* for voltage level up to 69 kV is less than or equal to 5.0%. Each individual harmonic voltage is limited to 3%. *ITHD* should be limited to a standard percent according to the system (I_{SC}/I_L) ratio.
- The shunt capacitor will be capable of continuous operation, provided that none of the following limitations are exceeded [11]: 135% of nominal rms current based on rated *kVA* and rated voltage, 110% of rated rms voltage, 120% of rated peak voltage, and135% of nameplate *kvar*.
- Maintaining the values of displacement power factor *Dpf* and the load power factor *PF* within an acceptable specified range ($\geq$ 90%) is desired.

Thus, the object function for *HPF* optimization, complying with the previous constraints, is presented as:

Minimize *H.P* (X_{CSH}, X_{LSH}, R_{SH}, and X_{SE}), subject to: (X_{CSH}, X_{LSH}, R_{SH}, and X_{SE}) not being part of Equations (14) and (15). Taking the solutions of these equations, the pre-considered compensator values are used to subdivide the entire search region into smaller regions. In each region, total minima are detected, leading to the final detection of the global minimum of the (H.P) ratio.

VI. CASE STUDIES AND RESULTS

Table I shows four cases primarily taken from [19] of two different short-circuit capacities (MVA$_{SC}$) of an industrial firm. The system data for equivalent single-phase mode are: The inductive loads power = 1700 kW, the inductive loads reactive power = 1655 kvar, and the 60- cycle supply phase voltage = 2.4 kV. Uncompensated system results are shown in Table II for comparison with *HPF* compensation results, where: I_S, V_L, and V_P are the rms values of the supply current, load voltage, and *PCC* voltage, respectively.

TABLE I
SYSTEM CASES [6]

Cases/Parameters	Case I	Case II	Case III	Case IV
MVA$_{SC}$	80		150	
R$_T$ (Ω)	0.02163	0.02163	0.01154	0.01154
X$_T$ (Ω)	0.2163	0.2163	0.1154	0.1154
R$_L$ (Ω)	1.7421	1.7421	1.7421	1.7421
X$_L$ (Ω)	1.696	1.696	1.696	1.696
V$_{S1}$ (V)	2400	2400	2400	2400
V$_{S5}$ (%V$_{S1}$)	4.00	4.00	4.00	4.00
V$_{S7}$ (%V$_{S1}$)	3.00	3.00	3.00	3.00
V$_{S11}$ (%V$_{S1}$)	2.00	2.00	2.00	2.00
V$_{S13}$ (%V$_{S1}$)	1.00	1.00	1.00	1.00
I$_{L1}$ (A)	922.56	922.56	951.93	951.93
I$_{L5}$ (A)	150	200	150	200
I$_{L7}$ (A)	100	150	100	150
I$_{L11}$ (A)	60	60	60	60
I$_{L13}$ (A)	30	30	30	30

The system analysis has been evaluated for different study system configurations that indicate the system performance with the proposed *HPF*, as shown in Table III. Furthermore, Tables IV and V show the performance of the *CPF* design presented in [6] and the traditional *SPF* design presented in [1], respectively, in order to show the effectiveness of the *HPF* in harmonic mitigation.

TABLE II
SYSTEM RESULTS BEFORE COMPENSATION [6]

Cases/Parameters	I	II	III	IV
PF (%)	69.96	68.79	70.17	69.12
Dpf (%)	71.65	71.65	71.65	71.65
I$_S$ (A)	938.71	951.41	969.35	983.01
V$_L$ (V)	2259.34	2267.86	2321.78	2324.39
H.P (%)	22.36	29.30	20.80	27.38

TABLE III
RESULTS FOR THE PROPOSED *HPF*

Cases/Parameters	I	II	III	IV
X_{CSH} (Ω)	2.937	2.700	3.469	2.701
X_{LSH} (Ω)	0.087	0.081	0.113	0.079
R_{SH} (Ω)	0.012	0.019	0.028	0.023
X_{SE} (Ω)	0.548	0.574	0.280	0.308
R_{SE} (Ω)	0.005	0.005	0.002	0.003
PF (%)	97.11	94.27	98.64	93.90
Dpf (%)	97.23	94.38	99.08	94.24
I_S (A)	730.79	757.75	714.23	757.50
V_P (V)	2410.52	2431.51	2393.28	2418.29
V_L (V)	2409.29	2429.11	2392.31	2416.92
H.P (%)	4.98	4.87	9.49	8.56

TABLE IV
RESULTS FOR THE *CPF* PRESENTED IN [6]

Cases/Parameters	I	II	III	IV
X_{CM} (Ω)	2.700	2.700	2.700	2.701
X (Ω)	0.153	0.129	0.19	0.162
R (Ω)	100.00	100.00	75.00	75.00
PF (%)	95.37	95.26	94.38	93.87
Dpf (%)	96.22	96.22	96.22	96.22
I_S (A)	748.30	749.19	753.14	757.20
V_L (V)	2424.50	2424.38	2415.37	2415.38
H.P (%)	13.34	14.20	19.89	22.51

TABLE V
RESULTS FOR THE *SPF* PRESENTED IN [1]

Cases/Parameters	I	II	III	IV
X_C (Ω)	4.844	4.383	4.205	4.786
X_F (Ω)	0.209	0.174	0.223	0.211
R (Ω)	0.017	0.015	0.016	0.017
PF (%)	95.91	97.11	96.73	94.24
Dpf (%)	96.96	98.37	98.93	97.16
I_S (A)	719.86	714.24	724.81	741.18
V_L (V)	2346.25	2357.05	2382.53	2373.72
H.P (%)	14.86	16.14	21.48	25.09

Comparison of the results given in Tables II to V shows that the optimization results are acceptable, providing an efficient system performance. Also, for the main target (H.P) suggested by [20] for the effectiveness of harmonic filters, it is obvious that installing the proposed *HPF* causes a remarkable reduction in the harmonic pollution ratio. This can be considered as a good sign for the significant fitness of the proposed hybrid passive filter in harmonic suppression. Thus the quality of the electrical system can be improved considerably. Fig. 3 shows that the total harmonic current distortion value of the compensated supply current is reduced to an acceptable limit, which could not be easily reached before with the conventional *SPFs*. This is considered to be a new contribution of the proposed hybrid passive filter. Figs. 4 and 5 show the simulated results of the optimization process of the compensated supply current harmonics content for cases I and III, respectively. The main contribution of the suggested method consists of the lower harmonic pollution of the supply current, compared to the response of the conventional *SPF*. Moreover, the *HPF* has a good capability for mitigation of the harmonic voltage distortion below the standard limits in all cases, as shown in Fig. 6 for the *VTHD* indication of the

compensated load voltage and Figs. 7 and 8 for the values of the compensated load voltage harmonics content in cases I and III, respectively.
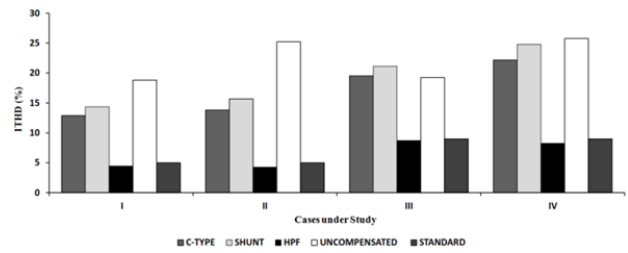

Fig.3. Total harmonic current distortion indication
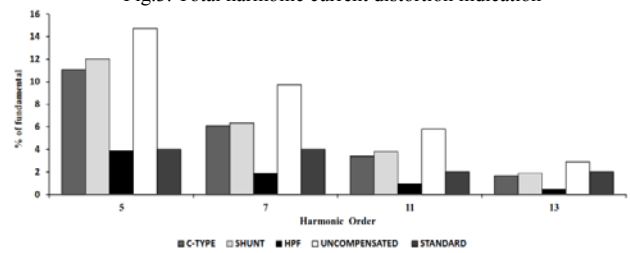

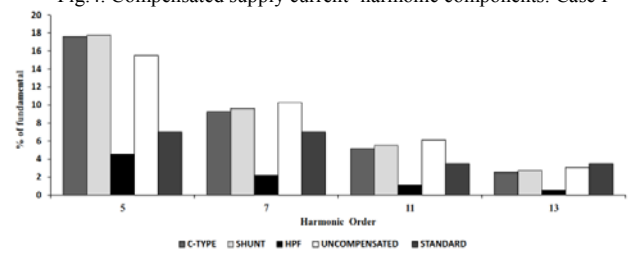Fig.4. Compensated supply current' harmonic components: Case I

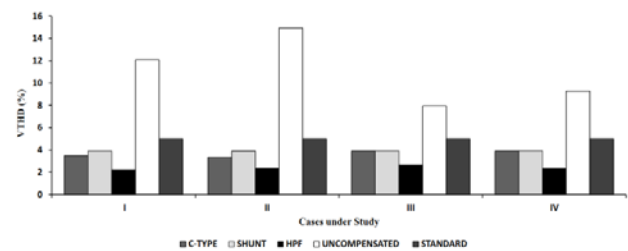Fig.5. Compensated supply current' harmonic components: Case III

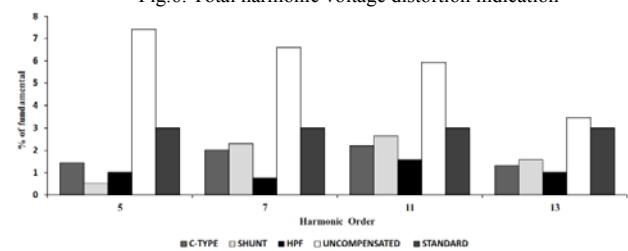Fig.6. Total harmonic voltage distortion indication

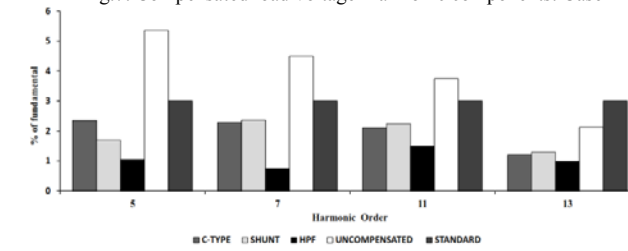Fig.7. Compensated load voltage' harmonic components: Case I

Fig.8. Compensated load voltage' harmonic components: Case III

Checking the voltage at the *PCC*, it is obvious that the *PCC* voltage complies with the limits in the IEEE Std. 519 (approximately equals 3.85% in all cases), as shown in Fig. 9, for all cases under study.
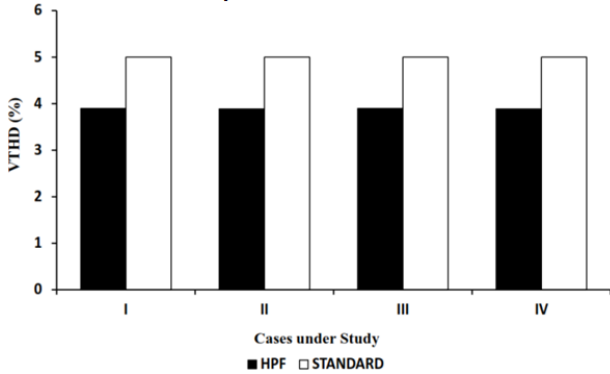

Fig.9. Total harmonic voltage distortion indication at the *PCC*

Referring to the capacitor loading constraints, it is notable that all values lie within the standard limits, as shown in Table VI, for all cases under study. If the resultant values are greater than standard limits, it is a good idea to use capacitors with a higher voltage rating [17].

TABLE VI
SHUNT CAPACITOR LOADING CONSTRAINTS

Parameters	Calculated (%)	Limit (%)	Exceeds Limit
Case I			
Rms voltage	103.29	110	No
Peak voltage	109.74	120	No
Rms current	106.03	135	No
kvar	116.36	135	No
Case II			
Rms voltage	104.30	110	No
Peak voltage	112.03	120	No
Rms current	108.28	135	No
kvar	120.31	135	No
Case III			
Rms voltage	103.06	110	No
Peak voltage	110.66	120	No
Rms current	106.96	135	No
kvar	118.36	135	No
Case IV			
Rms voltage	103.71	110	No
Peak voltage	111.63	120	No
Rms current	107.92	135	No
kvar	120.53	135	No

Based on the various models presented for constrained harmonic pollution minimization for nonlinear loads, it is obvious that, for equal MVA_{SC} systems with additional load current harmonics content, the reactive power supplied by the capacitor will increase, which will be reflected in the investment cost. The results shown in Table VI indicate that the capacitor loading requirements will be more stressed [6].

Lower MVA_{SC} systems with the same harmonic content will result in a lower *ITHD* level and harmonic pollution ratio owing to the great reduction in the current harmonics content. This is because of the additional series element of the *HPF*, which provides damping for the perturbations that can occur, which, in turn, improves the system stability.

For the proposed filter *HPF*, although it has similar structure to the conventional *SPF*, has a different operating principle. Unlike *SPFs* that employs a single tuned filter for each dominant harmonic to be mitigated, *HPF* employs only one shunt branch per phase and the filter absorbs a broad range of dominant harmonics. Table VII shows a comparison between the shunt portion of the *HPF* and the *SPF*, considering their quality factors and their corresponding bandwidth (B_P). It is obvious that the *HPF* has much broader B_P than the conventional *SPF*.

TABLE VII
COMPARISON OF *SPF* AND *HPF*, CONSIDERING *Q* AND B_P

Cases/Parameters	I	II	III	IV
HPF				
q	39.08	23.83	22.12	20.02
B_P (Hz)	8.93	14.64	15.01	17.54
SPF				
q	59.57	60.44	59.63	59.59
B_P (Hz)	4.85	4.98	4.37	4.79

Seeking clear demonstration of the proposed filter; performance of *HPF* for the parameter values given in Table III is simulated using software package of MatLab program. Figs. 10 and 11 show the waveforms of the supply current, load voltage, before compensation in case II, and case IV, respectively, while Figs. 12 and 13 show them after compensation, in addition to the voltage at *PCC* (V_P). It is obvious the remarkable reduction in the waveforms distortion. Fig. 14 shows filter impedance characteristics seen from the load side, for addressed cases, respectively, while, Fig. 15 shows the *k*th source side Thevenin impedance Z_k, series impedance ($Z_{Tk}+Z_{Ek}$) and the shunt portion impedance Z_{Hk} characteristics, for the same addressed cases. The tuning frequency of the shunt portion is between the 5*th* and 7*th* harmonic and the performance is not significantly dependent on it. Thus, the dominant harmonics are absorbed by the shunt portion on a broad range. The parallel resonance frequency of the *HPF* is a little below 140 Hz in cases I and II, and a little above 140 Hz in cases III and IV, thus the *HPF* exhibits only one resonance point safely above the second harmonic (which is greatly not likely to be excited). Fig. 15 shows that the series resonance frequency of the *HPF* is safely between the second and the third harmonic in the addressed cases. In the dominant harmonic frequency range; *HPF* and *SPF* have similar low impedance values. Additionally, Figs. 16 and 17 show the fast Fourier transform (FFT) analysis of the voltage at *PCC* for the addressed cases; it is notable that all values lie within the standard limits.

In a running plant, it is well-known that the switching inrush current of a transformer is rich in even and third harmonics. Also, source voltage harmonic contents may change [21], [22]; thus, eight additional scenarios are examined for the *HPF* parameters given in Table III: Case I; as follows:

Scenarios 1 to 4: considering an additional source voltage harmonic content of 3% *to:* V_{S2}, V_{S3}, V_{S4}, and V_{S6} respectively. *Scenarios 5 to 8:* considering an additional load current harmonic content of 30 amperes *to:* I_{L2}, I_{L3}, I_{L4}, and I_{L6}, respectively.

In a similar situation with *SPFs*, it is expected that the magnified currents can give rise to large harmonic voltages and shunt capacitors could also fail prematurely. Fig. 18 shows the variation of the *VTHD* at the *PCC*, and the *ITHD* of the source current, while considering the previous scenarios. It is obvious that almost 1% change occurs in the *VTHD* at the *PCC*, thus maintaining the allowable voltage quality, additionally, no substantial current harmonic amplification; also, it has a better total current distortion percent than *SPF*, subjected to the same conditions (although that the *HPF*'s efficiency is lowest at k=2). Furthermore, none of the shunt capacitor loading limits are exceeded with respect to the previous scenarios, as shown in Fig. 19 for the shunt capacitor duties, so no overloading occurs in the shunt capacitor.

The *HPF* series impedance isolates the effects of the line harmonic voltages on the load and the shunt portion of the filter. Furthermore, it attenuates the parallel resonance and blocks the series one with the utility and/or other loads. Thus, it offers more ability than other passive filtering methods [23] – [25]. Considering the expected cost of the *HPF*, Fig. 20 shows the expected total cost of the *HPF* compared to the other filters configurations under the same conditions, for all cases under study. It is obvious that *HPF* has an advantage as a reasonably competitive cost solution, especially when considering its ability to reduce the *VTHD* and the *ITHD* below the standard limits, and that harmonic-resonance risk is non-existent in *HPF*.
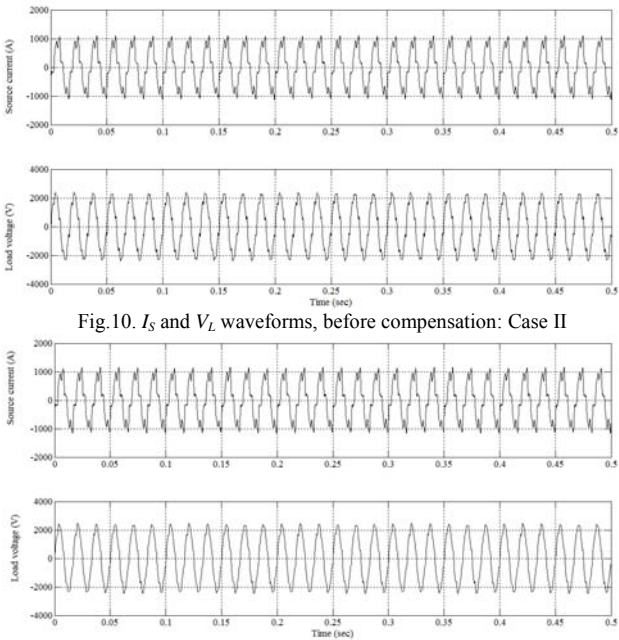

Fig.10. I_S and V_L waveforms, before compensation: Case II

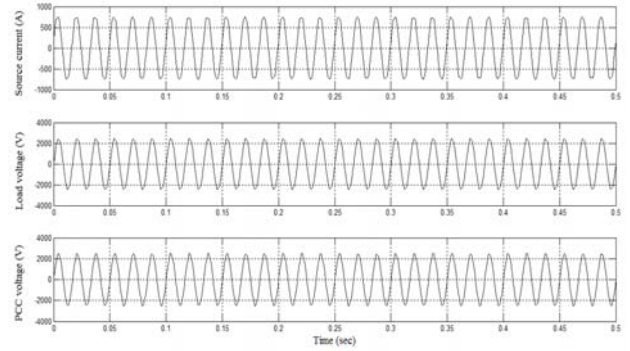Fig.11. I_S and V_L waveforms, before compensation: Case IV

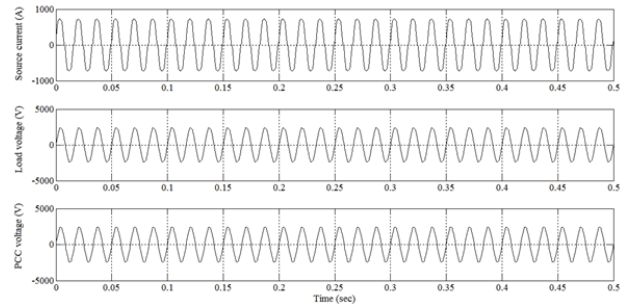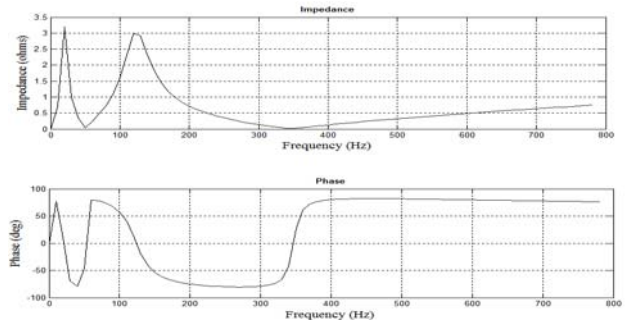Fig.12. I_S, V_L, and V_P waveforms after compensation: Case II

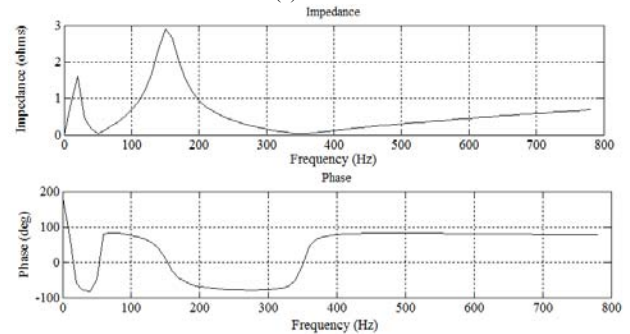
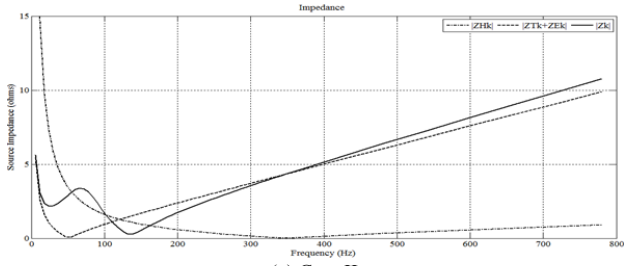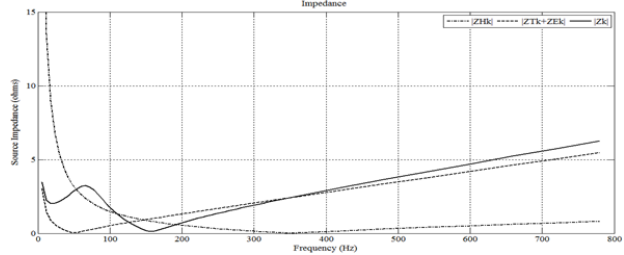Fig.13. I_S, V_L, and V_P waveforms after compensation: Case IV

(a) Case II

(b) Case IV
Fig.14. Impedance- frequency scans and phase-angle plots.
(a) Case II, (b) Case IV

(a) Case II

(b) Case IV

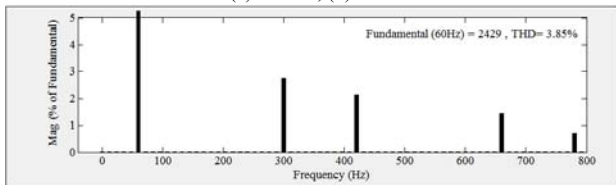Fig.15. Equivalent source impedance- frequency scans
(a) Case II, (b) Case IV

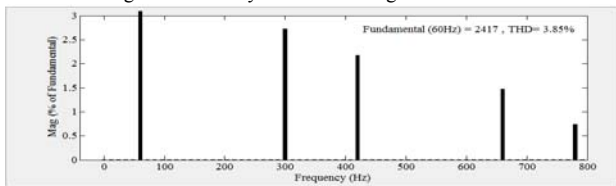Fig.16. *FFT* analysis for the voltage at *PCC*: Case II

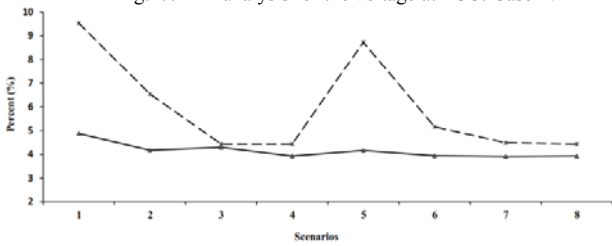Fig.17. *FFT* analysis for the voltage at *PCC*: Case IV
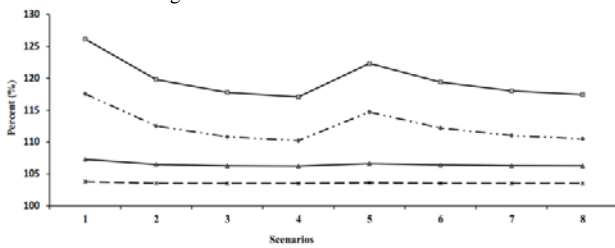

Fig.18. Variation in *VTHD* and *ITHD* at *PCC*
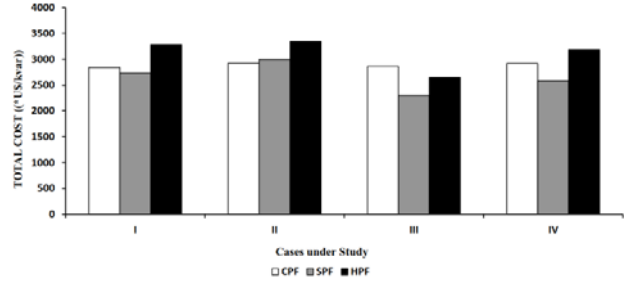

Fig.19. Variation in the shunt capacitor duties

Fig.20. Expected cost indication

Comparing to the adaptive passive filter proposed in [3], it is evident that both filters have the advantages of no harmonic-resonance risk, insensitivity to source-impedance variations, and low cost. However, the choice of the appropriate solution needs some awareness of the various topologies, requirements of the distorted system, and nature of loads. For example, in order to satisfy the requirements of randomly varying loads; the adaptive passive filter will be the best choice because of its fast dynamic response. In other cases with low penetration of random nonlinear loads or invariable-load reactive-power demand, the proposed *HPF* will be the most appropriate scenario, and hence the importance of the provided method in finding alternatives.

As with any new topologies, there is a lot of room for development. For example, more attention should be paid for the nonlinear interaction between the network and the nonlinear equipments. A first approach towards this would be to model the network as Norton model or Harmonic Coupled Norton Equivalent Model, with appropriate correlation functions. These models are more accurate for a wider range of operating conditions than the commonly used "constant current" model, especially when the source voltage *THD* is on the order of 10% or more. Moreover, calculations concerning the voltage drop and the joule losses will be taken into account in the analysis. The findings of this research will be presented in a future paper.

VII. CONCLUSION

Passive filters are still a growing concern for different customer sectors because they are considered to be powerful, easy, and economic solutions for power system harmonic suppression. Until now, harmonic suppression with fixed passive solutions has been carried out based only on mitigation of the harmonic voltage distortion, because it is not simple to meet acceptable harmonic current limits. However, the proposed *HPF* mitigates both currents' and voltages' harmonic pollution more effectively than other passive methods. The *HPF* can be considered as the first guard that stops the harmonic pollution propagation and offers isolation between the utility and the end-users. Consequently, it improves the performance efficiency and the life span of the electrical equipment. Finally, four cases are studied and the simulated results demonstrate the effectiveness of the proposed design procedure without any active strategy for complex control.

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