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Application of Single Tuned Passive Filters in Distribution Networks at the Point of Common Coupling

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***Abstract*—**The harmonic distortion of voltage is important in relation to power quality due to the interaction between the large diffusion of non-linear and time-varying single-phase and three-phase loads with power supply systems. However, harmonic distortion levels can be reduced by improving the design of polluting loads or by applying arrangements and adding filters. The application of passive filters is an effective solution that can be used to achieve harmonic mitigation mainly because filters offer high efficiency, simplicity, and are economical. Additionally, possible different frequency response characteristics can work to achieve certain required harmonic filtering targets. With these ideas in mind, the objective of this paper is to determine what size single tuned passive filters work in distribution networks best, in order to economically limit violations caused at a given point of common coupling (PCC). This article suggests that a single tuned passive filter could be employed in typical industrial power systems. Furthermore, constrained optimization can be used to find the optimal sizing of the passive filter in order to reduce both harmonic voltage and harmonic currents in the power system to an acceptable level, and, thus, improve the load power factor. The optimization technique works to minimize voltage total harmonic distortions (VTHD) and current total harmonic distortions (ITHD), where maintaining a given power factor at a specified range is desired. According to the IEEE Standard 519, both indices are viewed as constraints for the optimal passive filter design problem. The performance of this technique will be discussed using numerical examples taken from previous publications.

***Keywords*—**Harmonics, passive filter, power factor, power quality.

I. Introduction

IN power systems, the harmonic distortion of voltage and current waveforms has become a concern in recent years due to the widespread use of loads that produce currents with higher frequencies. This issue became more serious when a significant number of non-linear loads, including those of large capacity began to consume non-sinusoidal currents from systems, thus, distorting the voltage waveform, and having the potential to cause malfunction and overheating of the equipment in the power system [1], [2]. This scenario results in a degradation of the power factor (PF) of the load, thus increasing the risk of transmission line losses, and decreasing transmission system efficiency [3]. This scenario not only causes power losses but can also damage system components or reduce the life of grid equipment. Therefore, harmonic mitigation has become an issue for both utility companies and consumers alike. However, the most appropriate technical tools that can be used to decrease harmonic voltages are passive and active filters, and these are used to factor correction and harmonic mitigation [4], [5].

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II. Solutions to Harmonics Problems

Two main methods can be used to mitigate harmonics problems in order to improve power quality. Firstly, load conditioning can be undertaken; this means ensuring that electrical equipment is less sensitive to power disturbances, so as to allow operation under a significant voltage or current distortion. The second approach is to install line-conditioning systems that suppress power system problems [6].

TABLE I
COMPARATIVE PERFORMANCE BETWEEN PASSIVE AND ACTIVE FILTERS

Influences	Active filters	Passive filters
Increase in current	No risk	Risk
Control by filter order	Can be	Very difficult
Harmonic current control	Possible	Cannot be
Frequency variation	No effect	Effect
Modification in impedance	No effect	Risk
Modification in the fundamental frequency	Possible	Cannot be
Dimension	Small	Large
Weight	Low	High

Passive and active filters have been put forward as a solution [4], [7], [8] in relation to harmonic mitigation and reactive power compensation. The comparison between passive and active filters is tabulated in Table I [6]. In addition, it can be argued that active filters have superior performance for harmonic mitigation and for PF correction when compared to other types of harmonic filters [4]. Also, they do not introduce resonance that can move a harmonic problem from one frequency to another. However, active filters are not extensively used in the industry [9] mainly due to their high cost [4]. Furthermore, they require advanced control algorithms and complicated options to run, according to the circuit [10]-[12]. They are classed as one of the newest appropriate technical tools to use, and a number of different topologies are proposed [13]. As a result, passive filters are most widely used in power systems and are considered a better choice due to their simple structure, low running costs and high reliability. For this reason, they have been used in industrial facilities to ensure compliance with harmonic limits specified by supply utilities [8]. However, the performance of passive filters is limited and they can introduce resonance in the system. They are usually custom designed for application to each harmonic frequency [14]. In addition, if the parameters of the passive filter are improperly designed, then the filtering effect becomes worse, and so the initial investment cost may be increased, and reactive power may be over compensated, and so resonance may occur [15].

III. Passive Power Filter Topologies and Design Principle

Configurations of various types of passive filter and the common frequency responses of the filter types are shown in Figs. 1 and 2. [8]. Shunt connections for the passive power filters into the system (usually near the loads that produce harmonics) provide a low impedance path for the flow of harmonic current in comparison with a series connection. However, a series filter must carry a full load current as well as be insulated for full line voltage. It is worth mentioning that a single tuned passive filter is more practical than a harmonic filter, and is frequently sufficient for application due to the high costs of the series filter, and the fact that a shunt filter may supply reactive power at the fundamental frequency [16], [17].

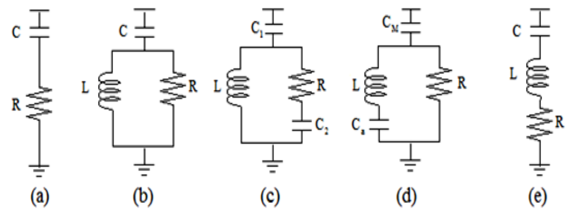

Fig. 1 Common shunt passive filter configurations - (a) first order, high-pass (b) second order, high-pass (c) third order, high-pass (d) C-type, and (e) the single-tuned filter

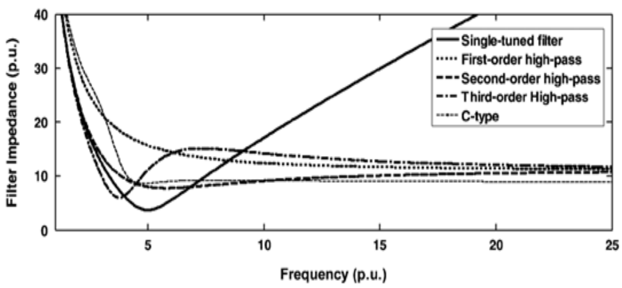

Fig. 2 Frequency response of common shunt passive filter configurations

In harmonics power systems, the limitation of harmonic distortion must be considered and applied at the PCC, between the utility supplier and the consumer. Therefore, certain standards determine the maximum allowable level for harmonics in the system. A harmonics filter generally has two purposes [6]: to reduce harmonic voltage and currents to below the permitted standard levels; and to provide reactive power to be absorbed. The overall aim is to comply with harmonic limits as defined in the IEEE Std. 519-1992 in order to provide economic incentives for encouraging utility firms and customers to provide and use electricity [18].

The general design principle of the passive filter is to achieve non-linear and multi-objective optimization, but achieving this is highly difficult. There are specific principles that should be considered in the optimal design, as:

- Avoiding compensator values that may cause series and parallel resonance. Also, the harmonic content should conform to international standards [19].
- The filter component ratings must be designed for the worst-case operating scenario in order to avoid damage and to meet technical requirements [20].
- When aiming for optimal design, the resistance of the compensator reactor can be neglected due to its small value, with respect to the magnitude of its fundamental reactance, and to satisfy a high quality factor (Q) circuit [19], [21]-[23].
- At the fundamental frequency, the size of filter can be determined by the reactive power supplied by the capacitors. The cost of the capacitor and inductor are assumed to be equal and proportional to their ratings [22].

IV. Single Tuned Passive Filter Equations

The general configuration of a single tuned passive filter is illustrated in Fig. 1 (e). It is composed of an inductor (L), a capacitor (C) and resistance (R) in a series where it offers very low impedance at the tuning frequency. Thus, all currents of that certain frequency will be deflected [24]. Its equivalent impedance Z as the function of the frequency can be expressed by:

$$Z(f) = R + j(\omega L - \frac{1}{\omega C}) \tag{1}$$

where $\omega = 2\pi f$ is an angular frequency, the impedance at the resonance frequency, the assumed part of (1) should be zero ($X_C = n^2 X_L$), where n is the harmonic number. Then, the resonant frequency of the single tuned element can be can be defined as shown in (2):

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

Choosing appropriate values for a capacitor, inductor and resistor, and ones that give an acceptable PF at line frequency, are essential for optimal filter design [7]. When this is done, the filter capacity and inductive values can be determined, as shown in (3) and (4):

$$C = \frac{1}{2\pi f_s X_C} \tag{3}$$

$$L = \frac{1}{(2\pi f_s)^2 h_0^2 C} \tag{4}$$

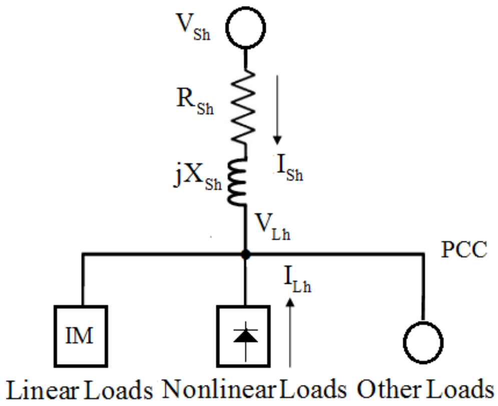

Fig. 3 The System under study

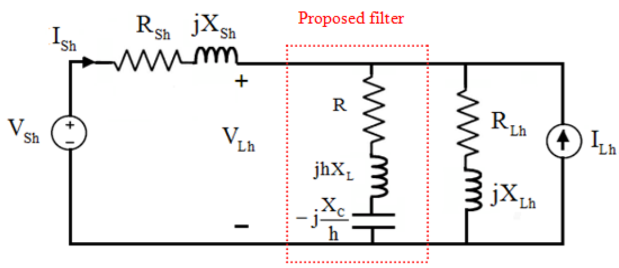

Fig. 4 Configuration of the Compensated System

where f_s represents the frequency of the supply mains, and h_0 represents the order of harmonics for which the filter is designed to tune [16].

The quality factor Q is the ability of the passive filter to draw the harmonic currents at the tuned frequency, and this reveals the sharpness of the resonance [25], as given in (5):

$$Q = \frac{\sqrt{LC}}{R} \tag{5}$$

V. Proposed System Configuration

Fig. 3 shows a single-phase diagram of a distorted bus of a typical balanced industrial system, where the linear loads shown represent a group of induction motors and other miscellaneous loads. Also, the nonlinear loads shown specifically represent DC drive loads, which are commonly represented by a current source model at their characteristic frequencies. The characteristic harmonic orders h and harmonic currents I_{Lh} injected by a line commutated converter operating under ideal conditions can be calculated as [19]:

$$h = k * p \pm 1 \tag{6}$$

$$I_{Lh} = \frac{I_1}{h} \tag{7}$$

where k is any integer number, and p is the pulse number of the converter.

Taking into account the single-phase equivalent circuit of the considered load bus, with the suggested single-tuned passive filter connected as shown in Fig. 4, the voltage, current and powers can be calculated.

The Thevenin voltage source for the mains and the harmonic current source, and the non-linear load, can be described as:

$$v_S(t) = \sum_h v_{Sh}(t) \tag{8}$$

$$i_L(t) = \sum_h i_{Lh}(t) \tag{9}$$

where v_{Sh} is the h^{th} harmonic source voltage.

Generally speaking, transmission power loss TL demonstrates losses between the sub-transmission network and low voltage connection points. In our case, this can be shown in losses caused by the resistive part of the Thevenin impedance.

$$TL = \sum_h I_{Sh}^2 R_{Sh}^2 \tag{10}$$

where I_{Sh} and R_{Sh} are the h^{th} harmonic Thevenin resistance, and the h^{th} harmonic line current, respectively

As a result, the VTHD and ITHD can be calculated as:

$$VTHD = \frac{\sqrt{\sum_{h>1}^{n} V_{Lh}^2}}{V_{L1}} *100 \tag{11}$$

$$ITHD = \frac{\sqrt{\sum_{h>1}^{n} I_{Sh}^2}}{I_{S1}} *100 \tag{12}$$

where subscript "1" stands for the fundamental harmonic order.

The algebraic manipulations for the system under study are shown in Fig. 4, where the voltage and current quantities, PF are used as an indicator of how effectively the power transmission and distribution equipment in power systems are utilised. This can be calculated as:

$$PF = \frac{P_L}{V_L I_S} \tag{13}$$

If the actual PF is to be improved, one should test the value of the displacement PF, or the PF at the fundamental frequency, as:

$$DPF = \frac{P_{L1}}{V_{L1} I_{S1}} \tag{14}$$

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where P_L is the uncompensated load active power per phase in watts (W)

To demonstrate system performance indications for a single tuned filter, the transmission efficiency η can be shown as:

$$\eta = \frac{P_L}{P_s} \tag{15}$$

where P_s is the supply active power.

VI. Optimal Filter Design Problem

In the optimal design of a single tuned passive filter, the total harmonic distortion (THD) can be a determinant for either minimizing voltage (VTHD) or minimizing current (ITHD). The overall design of the filter should be suitable to prevent harmonic malfunctions of system equipment. This paper aimed to discover the parameters of a passive filter for the minimization of THDI and THDV as a constraint, in order to comply with IEEE Standard 519-2014 [26]. There are limitations on several levels including both the short-circuit power of the system and the supply voltage. However, maximum transmission efficiency η , minimum transmission loss (TL), and *maximum a lagging PF with* a value between 0.95 and 1.00, were taken into account as constraints for optimal passive filter design.

Four different objective functions (OFs) with two numerical case studies taken from existing publications are considered in the optimal design of the proposed single-tuned shunt passive filter. They can be summarized as follows:

- OF.1: Maximizing the PF.
- OF.2: Minimizing the VTHD.
- OF.3: Minimizing the ITHD.
- OF.4: Minimizing the transmission losses (TL).

These OFs are selected to embrace most of the frequently used design goals of the passive filters.

VII. Simulated Results and Discussion

TABLE II
System Parameters

Parameters & Cases	Case 1	Case 2
Short-circuit power (MVA)	150	80
R_{S1} (Ω)	0.01154	0.02163
X_{S1} (Ω)	0.1154	0.2163
R_{L1} (Ω)	1.7421	1.7421
X_{L1} (Ω)	1.6960	1.6960
V_{S1} (V)	2400.00	2400.00
V_{S3} (%V_{S1})	0.00	0.00
V_{S5} (%V_{S1})	5.00	5.00
V_{S7} (%V_{S1})	3.00	3.00
V_{S11} (%V_{S1})	2.00	2.00
V_{S13} (%V_{S1})	1.00	1.00
I_{L3} (A)	304	304
I_{L5} (A)	33	33
I_{L7} (A)	25	25
I_{L9} (A)	26	26
I_{L11} (A)	8	8
I_{L13} (A)	9	9

Two cases of an industrial plant were simulated using optimization method. Data of an exemplary industrial system, used in IEEE Std. 519-1992 [27], are illustrated Table II.

The source and load harmonics of the four cases were chosen as presented in [28]. The inductive three phase loads are 5.1 MW and 4.965 Mvar. The 60-cycle supply bus voltage is 4.16 kV. The detailed plant loading is demonstrated in Table III.

TABLE III
Detailed Plant Loading

Load type	Active power (kw)	Reactive power (kvar)	*PF*
Induction motors	1200	900	0.8
	900	918	0.8
Thyristor DC Drives	600	612	0.7
	1100	1902	0.5
Other loads	1300	630	0.9
Total loading	5100	4965	0.7165

Table IV shows the uncompensated system results to be compared with the compensated system. All results are given in the single-phase mode. The uncompensated system results illustrate that the system cases have poor PFs, high TL, low load voltage values, and high line current values. Besides high percentages of the VTHD and ITHD are noticed.

TABLE IV
Uncompensated System Results

Parameters & Cases	Case 1	Case 2
PF (%)	68.37	68.37
DPF (%)	71.65	71.65
I_S (A)	995.41	963.19
V_L (V)	2321.14	2254.98
TL (kW)	11.43	20.07
η (%)	99.28	98.67
ITHD (%)	30.56	29.99
VTHD (%)	7.61	10.34

Tables V and VI illustrate the simulation results of the proposed filters without any constraints for the cases under study. It should be mentioned that the boxes in Gray represent the corresponding OFs.

TABLE V
Simulation Results of the System under Study, Case 1: Unconstrained Optimization

Parameters & Cases	No filter	OF. 1	OF. 2	OF. 3	OF. 4
X_C (Ω)	-----	3.94	0.12	0.19	3.94
X_L (Ω)	-----	0.44	0.07	0.08	0.44
PF (%)	68.37	99.25	3.37	3.37	99.25
DPF (%)	71.65	99.99	3.37	3.37	99.99
I_S (A)	995.41	709.09	155503.92	155502.77	709.09
V_L (V)	2321.14	2392.62	17797.19	17803.13	2392.59
TL (kW)	11.43	5.80	279054.16	279050.04	5.80
η (%)	99.28	99.66	25.07	25.08	99.66
ITHD (%)	30.56	11.55	0.14	0.11	11.56
VTHD (%)	7.61	4.53	0.04	0.38	4.53

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TABLE VI
SIMULATION RESULTS OF THE SYSTEM UNDER STUDY, CASE 2: UNCONSTRAINED OPTIMIZATION

Parameters & Cases	No filter	OF. 1	OF. 2	OF. 3	OF. 4
X_C (Ω)	-----	3.93	0.22	0.26	4.27
X_L (Ω)	-----	0.44	0.02	0.06	0.48
PF (%)	68.37	99.52	6.27	6.27	99.23
DPF (%)	71.65	99.99	6.27	6.27	99.71
I_S (A)	963.19	704.26	68193.87	68197.35	702.97
V_L (V)	2254.98	2381.69	14509.39	14498.47	2370.69
TL (kW)	20.07	10.73	100588.24	100598.50	10.69
η (%)	98.67	99.36	38.15	38.11	99.36
ITHD (%)	29.99	9.12	0.17	0.16	9.06
VTHD (%)	10.34	3.95	0.07	0.27	4.14

The previous results of the unconstrained optimization problems show that erroneous results are noticed for the optimization problems with OF. 2 and OF. 3. The system performance with these filters is worse than the system with no filters installed. Therefore, we concluded that the findings with these OFs indicate reasonable performance because of the acceptable PF percentages achieved. Accordingly, the systematic analysis has been repeated for the system under study via the tow optimization problems. The problems are reformulated to consider a nonlinear constraint that limits the PF within an acceptable specified range. Tables VII and VIII illustrate the simulation results of the proposed filters with the *PF* constrained for the two cases under study, respectively.

TABLE VII
SIMULATION RESULTS OF THE SYSTEM UNDER STUDY, CASE 1: CONSTRAINED OPTIMIZATION

Parameters & Cases	No filter	OF. 1	OF. 2	OF. 3	OF. 4
X_C (Ω)	-----	3.94	2.74	7.31	3.94
X_L (Ω)	-----	0.44	0.29	0.81	0.44
PF (%)	68.37	99.25	90.03	90.69	99.25
DPF (%)	71.65	99.99	90.78	91.13	99.99
I_S (A)	995.41	709.09	794.29	764.21	709.09
V_L (V)	2321.14	2392.62	2430.25	2357.79	2392.59
TL (kW)	11.43	5.80	7.28	6.74	5.80
η (%)	99.28	99.66	99.58	99.59	99.66
ITHD (%)	30.56	11.55	12.28	8.58	11.56
VTHD (%)	7.61	4.53	3.96	5.21	4.53

TABLE VIII
SIMULATION RESULTS OF THE SYSTEM UNDER STUDY, CASE 2: CONSTRAINED OPTIMIZATION

Parameters & Cases	No filter	OF. 1	OF. 2	OF. 3	OF. 4
X_C (Ω)	-----	3.93	2.70	7.31	4.27
X_L (Ω)	-----	0.44	0.29	0.81	0.48
PF (%)	68.37	99.52	91.71	90.79	99.23
DPF (%)	71.65	99.99	92.51	91.13	99.71
I_S (A)	963.19	704.26	789.53	750.46	702.97
V_L (V)	2254.98	2381.69	2447.93	2317.24	2370.69
TL (kW)	20.07	10.73	13.48	12.18	10.69
η (%)	98.67	99.36	99.25	99.23	99.36
ITHD (%)	29.99	9.12	9.26	7.36	9.06
VTHD (%)	10.34	3.95	3.25	4.90	4.14

The results demonstrate the validity and the effectiveness of the optimization method since the proposed techniques result in a notable reduction in the RMS value of the line current, so lower transmission loss and higher transmission efficiency are achieved. Also, acceptable PF percentages are achieved compared to the uncompensated system cases. The harmonic voltage components are considerably reduced compared to the uncompensated components for the cases under study. However, most of them do not meet the IEEE Standard 519 limits, in which each harmonic voltage component should not exceed 72 V (3%). Also, it is noted that reducing the harmonic voltage components will lead to a significant increase in the harmonic current distortion and vice versa, because of the nonlinear relationship between the harmonic voltages and currents.

Lower short circuit capacity systems with the same supply voltage harmonic contents and the same load harmonic currents (Cases 2 and 1) will result in lower RMS load voltage and lower line current passes to the compensated load. This is not the case for OFs. 2 and 3. Also, a significant increase in the TL will occur because of the higher transmission impedance.

Finally, it is noticed that different outcomes have been achieved via the OFs; this is mainly because of the nonlinearity of the optimization problems. Accordingly, using suitable constraints of the VTHD limits, individual harmonic distortion limits, and the capacitor loading limits, in addition to the PF and resonance constraints can significantly enhance the outcomes.

VIII. CONCLUSION

A systematic analysis has been assessed for different study system configurations that indicate the system performance with the shunt filter installed at the load side using multi-criteria goals, and with and without PF constraints. For the uncompensated system, a small harmonic current can cause a high voltage distortion. Accordingly, four different criteria for the optimal shunt passive filter design are discussed. These criteria were maximizing the load PF, and minimizing the VTHD, ITHD and transmission loss, respectively.

Based on the experience gained by studying and analysing the findings of each criterion for the harmonic passive filter design, the following points are concluded.

- Power system harmonics are an important topic in the quality of power issues because harmonics are steady-state periodic phenomena that produce continuous distortion of voltage and current waveforms due to the presence of nonlinear loads.
- Harmonic filter design should realize the optimal solution while satisfying many criteria. An important substitute to the multi-objective optimization is not to obtain the best solution, but to get a real compromise solution between the different conflicting power quality indices; this was evident in the optimal design results using the VTHD as an OF.
- One important side effect of using the single-tuned passive filters is that they create sharp parallel resonance.

Thus, this resonant frequency must be safely away from any significant harmonic. Ignoring the resonance in the analysis would lead to inaccurate results. Accordingly, the optimization problems should be reformulated to check for the filter solution that may cause resonance with the distribution system.

- Maximizing the load PF may reduce the harmonic voltage and harmonic current distortion, but may not minimize them below the standard limits.
- The passive filters can achieve the maximum permissible load PF. But, if the variation of the loading percentage is taken into account; it is more convenient to constrain the corrected load PF within a specified range of (90-95%).
- Based on IEEE standard 18-2012 [29]; capacitors are capable of safe, and continuous operation provided not to exceed 135% of the nominal RMS current, 110% of the nominal RMS voltage, and 135% of the nominal kvar. Compliance with these guidelines is imperative for capacitor banks as they are voltage-sensitive components of passive filters.

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