Harmonics Mitigation of Industrial Distributed Networks Using Harmonic Blocking Compensators

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Abstract **- This paper presents a passive harmonic blocking compensator (PHBC) for harmonic suppression and reactive power compensation in distribution systems. *PHBC* composed of a line series filter tuned to the fundamental frequency and a shunt passive filter. FORTRAN Feasible Sequential Quadratic Programming (FFSQP) is used as an optimization tool to find the proper sizing of parameters of the suggested filter for minimizing the supply current total demand distortion (TDD), where maintaining a given power factor at a specified range is desired. The optimal design of the *PHBC,* the contribution of the newly developed method and its feasibility are presented in two study cases.**

Index Terms – FFSQP, passive filters, power quality, power system harmonics.

I. NOMENCLATURE

FFSQP	FORTRAN Feasible Sequential Quadratic Programming
I_{Lk}	The load harmonic current at the *k*th harmonic order in amperes
I_{Sk}	The supply current at the *k*th harmonic order in amperes
I_S	Root-mean-square (rms) value of the supply current in amperes
G_{Lk}, B_{Lk}	Load conductance and susceptance in mhos at harmonic order k
PF	Load power factor in percent
P_{Loss}	The transmission losses per phase in watts
P_L	Load active power per phase in watts
R_{Lk}, X_{Lk}	Load resistance and reactance in ohms at harmonic order k
R_{Tk}, X_{Tk}	Thevenin source resistance and reactance in ohms at harmonic order k
V_{Lk}	Load voltage in volts at harmonic order k
V_L	Root-mean-square value of the load voltage (line-to-neutral) in volts
V_{Pk}	Point of common coupling voltage in volts at harmonic order k
V_P	Root-mean-square value of the point of common coupling voltage (line-to-neutral) in volts
V_{Sk}	Supply voltage in volts at harmonic order k
V_S	Root-mean-square value of the supply voltage (line-to-neutral) in volts
THDI	Total harmonic distortion of the supply current in percent
TDD	Total demand distortion of the supply current in percent
THD_{VL}	Total harmonic distortion of the load voltage in percent
THD_{VP}	Total harmonic distortion of the point of common coupling voltage in percent

II. INTRODUCTION

Power quality describes the quality of voltage and current. It is an important consideration in industries and commercial applications. During the last thirty years, much attention has been focused on power system harmonics. This is one of the most severe issues affecting power quality, because it affects both the utility company and consumers alike. Power system harmonics are considered to be the only issue with immediate effects, such as degradation of the power factor of the load, and overloading of conductors, but also some medium and long effects, such as reduction of life of the electrical equipment and early aging of insulators. Often when the subject of power quality arises and the harmful effects are recognized; industrial firms routinely suppose that the subject is related to harmonics [1].

Different researchers have studied the proper limitation of harmonic disturbance levels, and among several techniques used to reduce these harmonic disturbances, the most frequently managed are the tuned passive filters, due to their simplicity and economical cost [2], [3]. On the opposite side, further problems include importing harmonics by series resonance with source impedance, or the possibility of hazards due to parallel resonance between the source impedance and the passive filter at a specific frequency, could occur [4].

In this article, a proposed hybrid passive filter (PHBC) is demonstrated as a combination between series and shunt passive topologies to minimize both harmonic voltages and currents in the industrial distributed networks to an acceptable level at the point of common coupling (PCC), also improving the load power factor (PF) to an acceptable value (≥ 90%). *PHBCs* are built of a line series filter composed of series components L_{SE} and C_{SE}, which resonate at the fundamental frequency, and a conventional shunt passive filter. Due to the fundamental tuning branch, the series filter does not increase the line impedance for the fundamental. The shunt passive filter provides the connected loads with the reactive-power needed for power factor correction. It creates a low impedance shunt path for harmonic currents generated by the load [5], [6].

FFSQP optimization technique is used for optimal design and to establish the suitability and effectiveness of the *PHBC*. Sequential quadratic programming algorithms are widely recognized to be among the most successful algorithms for non-convex optimization. The FFSQP routine is held as a new approach for solving constrained nonlinear optimization problems, it guarantees many benefits. It has the ability to achieve reasonable solution accuracy and provides convergence to the global or near global solution [2], [7]. The performance of the FFSQP was examined in many applications [2], [3], [11]. Readers could refer to [7] for more information about the exact formulations of the FFSQP package.

II. Operating Principle of the Proposed Filter

Fig. 1 demonstrates the configuration of the proposed filter. Its series branch composed of series components L_{SE} and C_{SE}, which resonate at the fundamental frequency, in order to reduce the voltage drop for the fundamental harmonic. Fortunately, the series capacitor has no effects at higher frequency orders. The series portion acts as an isolator between the power system and the load and isolates the possible influences of the line harmonic voltages on the load and the filter [6]. In other words, the series filter provides effective separation of the load current and the distribution voltage harmonics and reduce any harmonic currents already presented. Furthermore, it damps the series and/or parallel resonance that may occur.

The series branch impedance Z_{Ek} at the *k*th harmonic order is given as follows:

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

The shunt filter has to provide reactive-power for the load compensation. The shunt branch impedance Z_{Hk} at the *k*th harmonic order is given as follows:

$$Z_{Hk} = R_{SH} + j(kX_{LSH} - \frac{X_{CSH}}{k}) \qquad (2)$$

For the shunt filter design; 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. In addition, the magnitude of the inductive reactance of the shunt portion X_{LSH} is related to X_{CSH} by the shunt tuned harmonic order, *h*, as follows:

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

$$X_{LSH} = \frac{X_{CSH}}{h^2} \qquad (4)$$

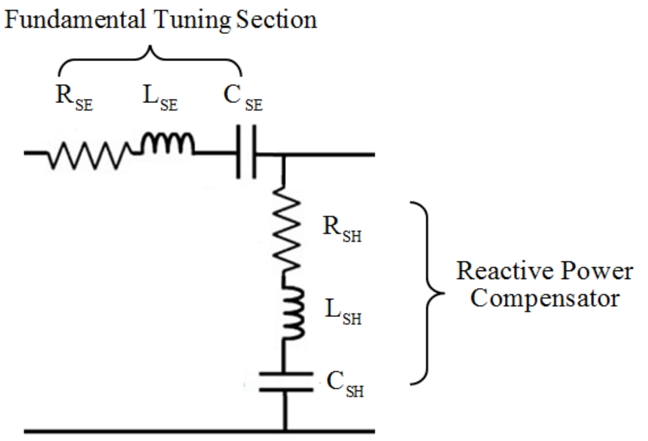

Fig.1 Proposed *PHBC* equivalent circuit

where: V_{L1} is the fundamental voltage at the shunt portion's bus. 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. Paradoxically, the fundamental value of the series inductance $|X_{SE}|$ should be relatively large to enhance the current quality [3]. Accordingly, $|X_{SE}|$ is given in various values of percent impedance as follows:

$$|X_{SE}| = m * Z_{BASE} \qquad (5)$$

where: *m* is an incremental factor varying with step of 0.01 and Z_{BASE} is the base impedance based on nominal load voltage and current [8].

In order to maintain simplicity; R_{SE} and R_{SH} are neglected because of their small values with respect to the magnitude of their fundamental reactances [1]-[3].

III. Configuration of the System Under Study

Fig. 2 shows a single-phase equivalent circuit of of a bus with the proposed passive compensator, experiencing voltage harmonic distortion at harmonic order (*k*) because of a voltage source V_{Sk} and harmonic current sources within the load itself I_{Lk}. To simplify the analysis, only the load model using the active and reactive powers at the fundamental frequency is considered while sizing the compensators.

The *k*th harmonic Thevenin source impedance is given as

$$Z_{Tk} = R_{Tk} + jX_{Tk} \qquad (6)$$

Also, the *k*th harmonic load impedance is given as

$$Z_{Lk} = R_{Lk} + jX_{Lk} \qquad (7)$$

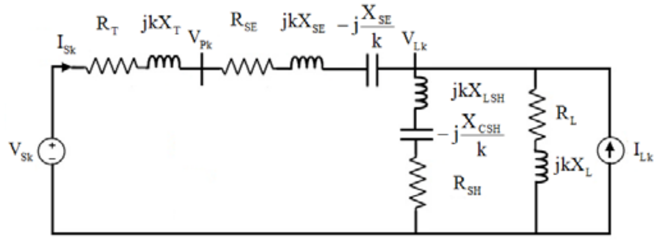

Fig.2 Configuration of the system under study

The compensated supply current I_{Sk} at harmonic order (*k*) is given as

$$I_{Sk} = \frac{\left[V_{Sk}(R_{SH}+R_L)+I_{Lk}C_3\right]+j\left[V_{Sk}\left(C_5+kX_L\right)+I_{Lk}C_4\right]}{[E]+j[F]} \quad (8)$$

The compensated point of common coupling (PCC) voltage (V_{Pk}) at harmonic order (*k*) is given as:

$$V_{Pk} = \frac{[T_1]+j[T_2]}{[E]+j[F]} \quad (9)$$

Also, the compensated load voltage V_{Lk} at harmonic order (*k*) is given as:

$$V_{Lk} = \frac{\left[V_{Sk}C_3 - I_{Lk}A\right]+j\left[V_{Sk}C_4 - I_{Lk}B\right]}{[E]+j[F]} \quad (10)$$

where

$A = C_1R_{SH} - C_2C_5 - C_4C_6, B = C_1C_5 + C_2R_{SH} + C_3C_6,$

$T_1 = V_{Sk}\left(C_3 - C_6\left(C_5 + kX_L\right)\right) - I_{Lk}\left(C_1R_{SH} - C_2C_5\right),$

$T_2 = V_{Sk}\left(C_4 + C_6\left(R_{SH} + R_L\right)\right) - I_{Lk}\left(C_1C_5 + C_2R_{SH}\right),$

$E = \left(C_1 + R_{SH}\left(R_T + R_L\right)\right) - \left(C_5X_{TL}\right) - \left(C_6\left(C_5 + kX_L\right)\right),$

$F = \left(C_2 + R_{SH}X_{TL}\right) + \left(C_5\left(R_T + R_L\right)\right) + \left(C_6\left(R_L + R_{SH}\right)\right),$

$C_1 = R_TR_L - k^2X_TX_L, \ C_2 = R_TkX_L + R_LkX_T,$

$C_3 = R_{SH}R_L - C_5kX_L, C_4 = R_{SH}kX_L + C_5R_L,$

$C_5 = kX_{LSH} - \frac{X_{CSH}}{k}, C_6 = X_{SE}(k - \frac{1}{k})$, and

$X_{TL} = k\left(X_T + X_L\right).$

The compensated load power factor *PF* at is given as

$$PF = \frac{\sum_k G_{Lk}V_{Lk}^2}{\sqrt{\sum_k I_{Sk}^2 \sum_k V_{Lk}^2}} \quad (11)$$

where G_{Lk} is the load conductance in mho at harmonic order *k*.

The transmission losses (P_{LOSS}) are given as:

$$P_{LOSS} = \sum_k I_{Sk}^2 R_T \quad (12)$$

To identify the harmonic content of the compensated point of common coupling (PCC) voltage and the compensated load voltage; total voltage harmonic distortion (THD_{VP}) and (THD_{VL}) have been introduced. They are given as

$$THD_{VP} = \frac{\sqrt{\sum_{k\succ 1} V_{Pk}^2}}{V_{P1}} \quad (13)$$

$$THD_{VL} = \frac{\sqrt{\sum_{k\succ 1} V_{Lk}^2}}{V_{L1}} \quad (14)$$

Similarly, for the compensated supply current, total harmonic distortion (THD_I) and total demand distortion (TDD) are given as

$$THD_I = \frac{\sqrt{\sum_{k\succ 1} I_{Sk}^2}}{I_{S1}} \quad (15)$$

$$TDD = \frac{\sqrt{\sum_{k\succ 1} I_{Sk}^2}}{I_L} \quad (16)$$

IV. Formulation of Objective Function and Constraints

Minimization of TDD is proposed as an objective for the optimal filter design problem. Individual harmonics and total harmonic distortions of the voltage and current measured at the PCC are considered as constraints for the proposed filter design due to the harmonic limitations given in IEEE Standard 519–1992. Additionally, maintaining the values of the load power factor within an acceptable specified range (≥ 90%) is desired. Furthermore, according to IEEE std. 18-2002 [10]; the shunt capacitor will be capable of continuous operation, provided that none of the following limitations are exceeded: 135% of nominal rms (root-mean-square) current based on rated kVA and rated voltage, 110% of rated rms voltage, 120% of rated peak voltage and135% of nameplate kvar. Thus, the optimal design problem of the proposed filter can be written as follows:
Minimize *TDD* (X_{CSH}, X_{LSH}, and X_{SE}), subject to the following constraints:

$90 \le$ PF (X_{CSH}, X_{LSH}, and X_{SE}) $\le 100\%$,

$0 \le THD_{VP}$ (X_{CSH}, X_{LSH}, and X_{SE}) $\le 5\%$

$0 \le THD_{VL}$ (X_{CSH}, X_{LSH}, and X_{SE}) $\le 5\%$

$0 \le V_{Pk, k\neq 1}$ (X_{CSH}, X_{LSH}, and X_{SE}) $\le$ Max V_{Pk}

$0 \le V_{Lk, k\neq 1}$ (X_{CSH}, X_{LSH}, and X_{SE}) $\le$ Max V_{Lk}

$0 \le$ TDD (X_{CSH}, X_{LSH}, and X_{SE}) $\le 5\%$

$0 \le I_{Sk, k\neq 1}$ (X_{CSH}, X_{LSH}, and X_{SE}) $\le$ Max I_{Sk}

In addition to the loading duties of the shunt capacitor:
Rms current (X_{CSH}, X_{LSH}, and X_{SE}) ≤ 135%, rms voltage (X_{CSH}, X_{LSH}, and X_{SE}) ≤ 110%, peak voltage (X_{CSH}, X_{LSH}, and X_{SE}) ≤ 120% and reactive-power (X_{CSH}, X_{LSH}, and X_{SE}) ≤ 135%
These constraints avoid the compensator values that would create resonance.

V. The Search Algorithm

FFSQP first suffices a feasible point complying with the constraints; subsequently the followed iterations provided by FFSQP all satisfy these constraints. Also, nonlinear equality constraints are converted into inequality constraints (to be satisfied by all iterations) and the maximum of the objective functions is replaced by an exact penalty function, which penalizes nonlinear equality constraint violations only. The proposed search algorithm is demonstrated below. Additionally, Fig. 3 shows a general flow-chart for the search algorithm.

1. Determine the specifications of the FFSQP subroutine and construct the needed subroutines to develop the FFSQP search.
2. Choose the first value of factor *m*; it is varying in the range (0.01–0.25) with a step of 0.01 and calculates X_{SE} from (5).

3. Choose the first value of the standard manufactured reactive power rating of capacitors in kvar.

$$Q_{Ci} = \{Q_{C1}, Q_{C2}\ldots Q_{Cj}\}$$

where *j* is the number of discrete values available for the particular voltage rating used and *i* has a starting value of 1.

4. Calculate X_{CSHi} for a *PHBC* from (3), and substitute the first value of X_{CSHi} into (4) for X_{LSHi}. Substitute the values of X_{SHi}, X_{LSHi} and X_{SE}, into the objective function, and calculate the minimum (*TDD*), while complying with the constraints and checking for the THD_{VL} and THD_{VP} values.
5. Run the search algorithm considering the filter components values to be the initial values at the beginning of each search. Repeat with the second value of *m* at the same Q_{Ci}, (e.g. m = m + 0.01). Using the search algorithm to solve the objective function for minimum *TDD* while complying with the constraints.
6. If *i* = *j* stop, otherwise replace *i* by (i + 1), and go to step 1. The algorithm will stop when a feasible point is reached.
7. After stopping, scan through local minimums to get the global one. Determine the compensator parameters values corresponding to the global solution. Use the obtained optimum values to evaluate some other functions which explain the system performance when installing a *PHBC*.

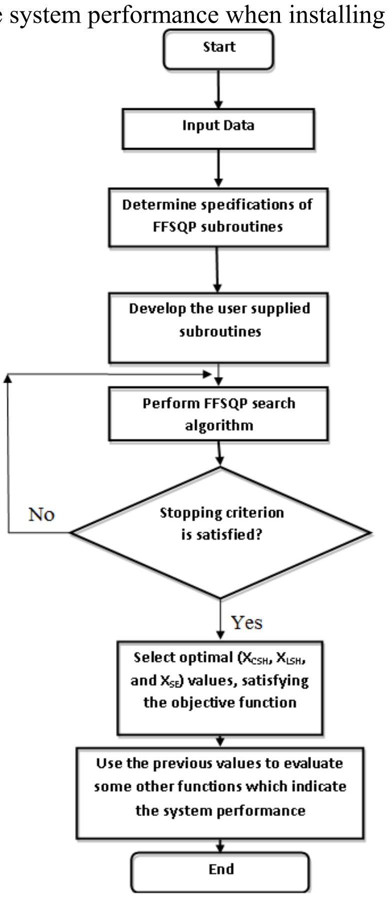

Fig. 3 General flow-chart for the search algorithm using FFSQP

VI. Case Studies and Results

Two cases of an industrial plant were provided using the FFSQP optimization method. The numerical data were taken from an example in IEEE publications [9], where the inductive three-phase loads are 5100 kW and 4965 kvar. The 60-cycle supply bus voltage is 4.16 kV (line-to-line), 80 MVA short circuit capacity. The system data for equivalent single-phase mode are [1]: Thevenin source resistance R_{T1} = 0.02163 Ohms. Thevenin source reactance X_{T1} = 0.2163 Ohms. Load resistance R_{L1} = 1.7421 Ohms. Load reactance X_{L1} = 1.696 Ohms. Maximum demand load current (I_L) =988 Amperes. MVA_{SC} / MVA_L = 11.24.

Table I shows the source and load harmonics, they were assumed to be time-invariant quantities. Table II shows the uncompensated system results to be defined and compared with *PHBC* compensation results. Table III shows the compensated system results that indicate the system performance with the *PHBC* installed at the load side.

TABLE I
Harmonic Content of the Two Cases of the Industrial Plant under Study

Parameters and Harmonics	Case 1	Case 2
V_{S5} (%V_{S1})	4.00	5.00
V_{S7} (%V_{S1})	2.00	3.00
V_{S11} (%V_{S1})	1.00	2.00
V_{S13} (%V_{S1})	0.5	1.00
I_{L5} (A)	100	200
I_{L7} (A)	70	100
I_{L11} (A)	30	50
I_{L13} (A)	10	25

TABLE II
Uncompensated System Results

Parameters	Case 1	Case 2
PF (%)	70.91	69.37
I_S (A)	929.62	945.72
V_L (V)	2250.14	2262.30
P_{LOSS} (kW)	18.69	19.35
THD_{VL} (%)	8.00	13.14
THD_{VP} (%)	8.00	13.14
THD_I (%)	12.42	22.56
TDD (%)	11.45	20.81

TABLE III
Simulated Results in the Two Cases for the *PHBC*

Parameters	Case 1	Case 2
X_{CSH} (Ω)	2.846	2.701
X_{LSH} (Ω)	0.134	0.091
X_{SE} (Ω)	0. 692	0.391
PF (%)	95.88	93.46
I_S (A)	742.72	764.94
V_L (V)	2417.37	2426.88
V_P (V)	2418.40	2422.22
P_{LOSS} (kW)	11.93	12.66
THD_{VL} (%)	1.98	2.05
THD_{VP} (%)	3.52	3.90
THD_I (%)	3.18	6.19
TDD (%)	2.36	4.66

Comparison of the results given in Tables II and III show that the optimization results are acceptable, providing improvement in the system performance. Table III shows that the proposed filter results in higher load power factor and lower P_{LOSS} thus higher transmission efficiency compared to the uncompensated system cases. Figs. 4 and 5 show the values of the harmonics content of the load voltage after compensation for cases 1 and 2, respectively. Figs. 6 and 7 show the values of the harmonics content of the voltage at the *PCC* after compensation for cases 1 and 2, respectively. Figs. 8 and 9 show the values of the harmonics content of the supply current after compensation for cases 1 and 2, respectively. It is obvious that the resultant values all come out well within standard limits. It can be clearly noticed that for both cases, the proposed design approach results in lower THD_I and THD_{VP} values when compared with the uncompensated system results.

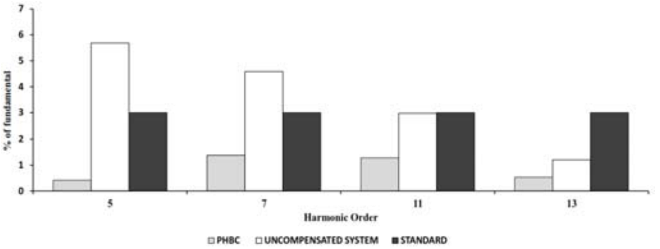

Fig. 4 The load voltage' harmonics content before and after compensation: Case 1

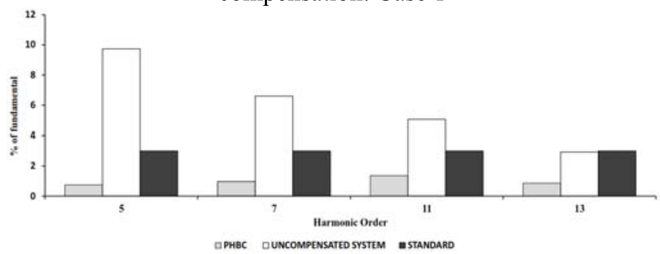

Fig. 5 The load voltage' harmonics content before and after compensation: Case 2

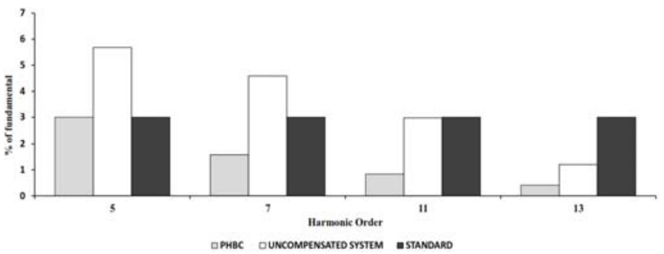

Fig. 6 Voltage at the PCC' harmonics content before and after compensation: Case 1

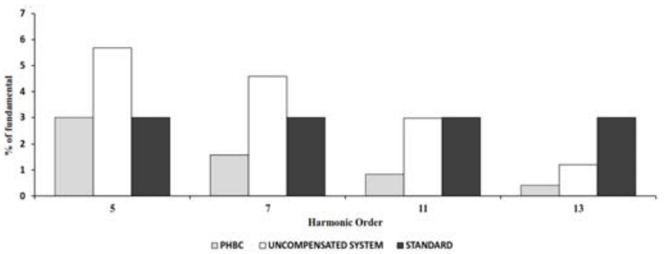

Fig. 7 Voltage at the PCC' harmonics content before and after compensation: Case 2

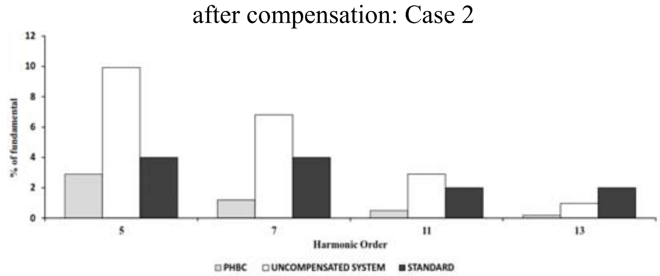

Fig. 8 The supply current' harmonics content before and after compensation: Case 1

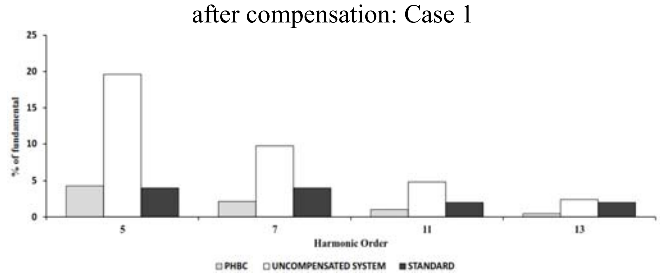

Fig. 9 The supply current' harmonics content before and after compensation: Case 2

IEEE Standard 18-2002 specifies the pre-discussed continuous capacitor ratings; Table IV shows the calculated capacitor limits compared with the IEEE Standard 18-2002 limits for all cases. Comparison of the calculated and standard limits shows that all values lie within the standard limits.

TABLE IV
MAIN CAPACITOR DUTIES

Item	Calculated (%)	Limit (%)	Exceeds Limit
Case 1			
Rms voltage	105.94	110	No
Peak voltage	109.66	120	No
Rms current	106.86	135	No
kvar	117.18	135	No
Case 2			
Rms voltage	104.89	110	No
Peak voltage	111.68	120	No
Rms current	108.11	135	No
kvar	120.73	135	No

Figs. 10 and 11 show the frequency spectrum of the system-equivalent impedance seen from the harmonic source side for cases 1 and 2, respectively. The resonant frequency of the shunt portion is around 300 Hz (fifth harmonic order) and the filter performance is not significantly dependent on it. This is because the blocking series filter attenuates the line harmonic currents and isolates the possible effects of the harmonic voltages on both the load and filter. Higher dominant harmonics are mitigated by the shunt filter on a broad range. On the opposite side, the parallel-resonance frequency of the proposed filter is around 140 Hz in both cases, thus resonance chances is greatly not likely to be excited [11].

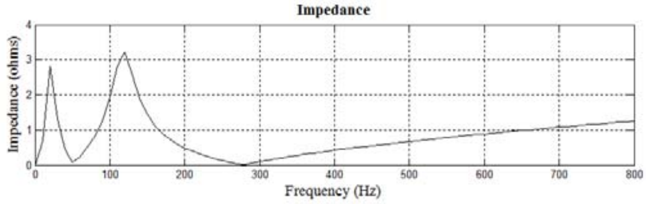

Fig. 10 Equivalent impedance- frequency scan: Case 1

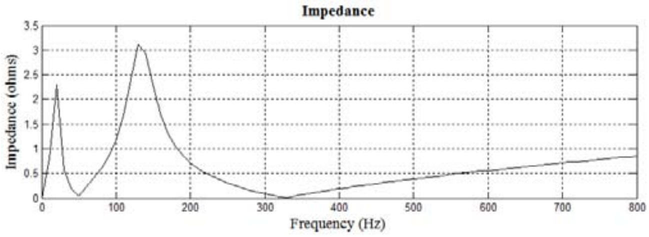

Fig. 11 Equivalent impedance- frequency scan: Case 2

Finally, two cases are studied and the simulated results demonstrate the effectiveness of the proposed design procedure. Based on the experience gained from this study, the results show that harmonic blocking filters are effective compensators in mitigation of harmonic distortion. This is because that they do not suffer from the resonance problems of conventional shunt passive filters. Furthermore, they have a better current quality than other passive filtering methods [12], [13]. However, power losses and voltage drop in the series filter are shortcomings to the harmonic blocking compensators. Additional constraints concerning them must be taken into account before taking a final decision about this type of filters.

VII. CONCLUSIONS

This article presents a passive harmonic blocking compensator for harmonic suppression and reactive power compensation in industrial distribution network. The contribution of the developed method and the general system performance when using this kind of filters are demonstrated and discussed. As with any new methodology, there are a lot of points must be taken into consideration. The most important are the additional power losses, voltage drop and the more concern for manufacturing tolerance in the series portion of the blocking compensator.

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REFERENCES

[1] S. H. E. Abdel Aleem, A. F. Zobaa, and A. C. M. Sung, “On the economical design of multiple-arm passive harmonic filters,” *in 47th International Universities' Power Engineering Conf.*, UPEC’12, Uxbridge, Middlesex, United Kingdom, Sep. 4–7, 2012, pp. 1–6.

[2] S. H. E. Abdel Aleem, A. F. Zobaa and M. M. Abdel Aziz, “Optimal C-Type Passive Filter Based on Minimization of the Voltage Harmonic Distortion for Nonlinear Loads,” *IEEE Trans. Ind. Electron.,* vol. 59, no.1, pp. 281–289, Jan. 2012.

[3] A. F. Zobaa, M. M. Abdel-Aziz, and S. H. E. Abdel Aleem, "Comparison of shunt-passive and series-passive filters for DC drive loads," *Electric Power Components & Systems*, vol. 38, no. 3, pp. 275–291, Mar. 2010.

[4] F. C. De La rosa, Harmonics and power systems, Distribution Control Systems, 1st ed., Taylor & Francis Group, New York, U.S.A., 2006.

[5] L. S. Czarnecki, “An Overview of Methods of Harmonic Suppresion in Distribution Systems,” *2000 IEEE Power Engineering Society Summer Meeting*, PES’00, Seattle,Washington, USA, Jul. 16–20, 2000, pp. 800-805.

[6] L. Luo, Y. Li, J. Xu, J. Li, B. Hu, and F. Liu, "A new converter transformer and a corresponding inductive filtering method for HVDC transmission system," *IEEE Trans. Power Del.,* vol. 23, no. 3, pp. 1426–1431, Jul. 2008.

[7] J. L. Zhou, A. L. Tits, and C. T. Lawrence, *User's guide for FFSQP version 3.7: A FORTRAN code for solving optimization problems, possibly minimax, with general inequality constraints and linear equality constraints, generating feasible iterates*, TR-92-107r5, Institute for Systems Research, University of Maryland, College Park, MD20742, USA, 1997.

[8] M.Z. El-Sadek, *Power Systems Harmonic Filters*, 1st ed., Muktar Press, Assiut, Egypt, 2007.

[9] *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems,* IEEE Standard 519–1992, 1992.

[10] *IEEE Standard for Shunt Power Capacitors,* IEEE Standard 18-2002, 2002.

[11] S. H. E. Abdel Aleem and A. F. Zobaa, “A New Approach for Harmonic Distortion Minimization in Power Systems Supplying Nonlinear Loads,” *IEEE Trans. on Ind. Electron.,* in press.

[12] I.P. Abril and J.A.G. Quintero, “VAR compensation by sequential quadratic programming,” *IEEE Trans. Power Sys.*, vol.18, no.1, pp. 36–41, Feb. 2003.

[13] L. Sainz and J. Balcells, “Harmonic Interaction Influence Due to Current Source Shunt Filters in Networks Supplying Nonlinear Loads,” *IEEE Trans. Power Del.*, vol.27, no.3, pp.1377–1385, Jul. 2012.