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Economical Design of Capacitive Components of Multiple-Arm Shunt Passive Harmonics Filters

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***Abstract* –low power factors and harmful effects of power system harmonics are major concerns nowadays. Design engineers recommend passive harmonic filters use due to their simplicity and cost. This paper addresses different economical methods to calculate the capacitive components of multiple-arm shunt passive harmonic filters considering non-sinusoidal environment. The essential aspects required for the filter design, merits and drawbacks are illustrated and compared with other published techniques by means of two different case studies.**

***Index Terms* – power systems harmonics, distortions, power factor, passive filters, power quality.**

I. Introduction

Loads power factors are determinant factors in defining power quality and voltage stability. The concept of high power factor is important to efficient use of electrical energy and higher quality of power system operation. On the contrary, low load power factor increases the probability of service interruption, hence; reduction of the network efficiency and reliability are expected; also the level of the harmonic distortion in distribution networks will increase considerably [1].

In recent years, much attention has been focused on simplifying the commonly used solutions regarding the harmonic contamination associated with low loads power factors in power systems. Different solutions are being proposed to enhance the practical utilization of harmonic filters. One of the most managed solutions in the power quality market is the use of shunt passive filters either alone or combined with other types of harmonic filters as an economical solution for power factor improvement and harmonics suppression; providing direct benefits for both the utility company and consumers alike [2]-[4].

Theoretically, a single tuned harmonic passive filter is installed for each harmonic needed to be restricted. Together they form a harmonic passive filter bank to keep up the harmonic distortion below allowable limits. An industrial efficient filter is proposed to mitigate power system harmonics at the least possible cost and provides reactive power [5]. In this manner, the selection of relative size of capacitor values of multiple-arm passive harmonic filters is usually a matter of trial and error. Commonly, it is suggested that all capacitors values are equal because of the simplicity of that method and the expected good performance in some cases. Unfortunately, it was obvious from real practice that this method hasn't met the acceptable, economical and technical requirements of the power quality markets, especially with highly distorted loads [6]. Recently, several methods for the selection of relative size of capacitor values of multiple-arm passive filter design had been introduced in [7]. Each method has some advantages and drawbacks. Conversely, it is clear that different conditions must be considered before making the final decision on a filter configuration based on these strategies such as voltage level, distortion percent, and the amount of the reactive power required to be supplied.

In this paper, an optimal method depends on the design of the passive harmonic filter parameters on an economical basis to ensure minimum cost and minimum losses had been carried out, considering various load distortion percents. This paper is written to assist electrical power system installation designers in identifying the performance of the proposed economical method, advantages, drawbacks, and usage bounds compared with the deep-rooted equal capacitance method by means of two numerical examples.

II. Cost Estimation for Passive Filter Multiple-Arms

The following objective topologies are considered in the design of the proposed multiple-arm of a harmonic passive filter:

A. *Equal Capacitance Method:*

The total capacitance required (C_{Total}) for power factor correction is split equally among the filter arms [8]. This is considered the general and the simplest method.

B. *Optimal Capacitance Method:*

Based on mathematical manipulation; optimal values of capacitance can be calculated, in order to guarantee minimum cost and satisfy the specified improvement of the load power factor. For a specified bus under consideration for installing passive filter, the filter size (S_K) is determined by the reactive power supplied by the capacitors at the fundamental frequency [7]. If the filter is connected for a harmonic order (K); the total capacitive reactive power (Q_{CK}) in terms of the filter size (in megavars) for this filter arm is given by

$$Q_{CK} = a_K \left[S_K + \frac{V_1^2 I_K^2}{K S_K} \right] \quad (1)$$

where $a_K = \frac{K^2}{K^2 - 1}$.

V_1 is the fundamental line to neutral voltage and I_K is the harmonic current passing through the filter arm at the specified harmonic order. Thus, the capacitor cost (C_C) in Egyptian pounds (L.E.) can be calculated as follows:

$$C_C = U_C \left[Q_{CK} \right] \quad (2)$$

where U_C is the capacitor unit cost given in (L.E./Mvar).

Similarly, the total inductive reactive power (Q_{LK}) in terms of the filter size for this filter arm is given by

$$Q_{LK} = a_K \left[\frac{S_K}{K^2} + \frac{V_1^2 I_K^2}{K S_K} \right] \quad (3)$$

The inductor cost (C_L) in Egyptian pounds can be calculated as follows:

$$C_L = U_L \left[Q_{LK} \right] \quad (4)$$

where U_L is the reactor unit cost given in (L.E./Mvar). In order to maintain simplicity; the reactor unit cost (U_L) and the capacitor unit cost (U_L) are assumed to be equal and proportional to their ratings [5].

Reference [9] summarizes the steps of calculation of the energy losses cost (C_E) in Egyptian pounds as follows:

$$C_E = 7274.3 * a_K \left[S_K + \frac{V_1^2 I_K^2}{K S_K} \right] \quad (5)$$

The constant included within the previous equation is chosen primarily based on Egyptian tariff parameter concerns [8]. In which the subsequent parameters are considered:

- Filter lifetime = 15 years
- Capacitor unit cost (U_C) = 10^5 L.E./Mvar
- Reactor unit cost (U_L) = 10^5 L.E./Mvar
- Filter utilization factor = 1.0
- Cost of power loss = 0.20 L.E./kWh
- Interest value factor = 0.05
- Loss factor of the capacitor = 0.4 kW/Mvar
- Power loss through filter's arm resistance are neglected; because of the small value of the resistance of the compensator reactor with respect to the magnitude of its fundamental reactance in a high quality factor (Q) circuit [10], [11].

Hence, the filter cost (C_F) in Egyptian pounds is given by

$$C_F = C_C + C_L + C_E \quad (6)$$

Substituting (2), (4) and (5) in (6) and arranging in terms of the filter size; leads to:

$$C_F = A\left[S_K\right] + B\left[\frac{1}{S_K}\right] \quad (7)$$

so that

$$A = a_K * 10^5 \left[\frac{1}{K^2} + 1.07 \right] \quad (8)$$

$$B = a_K^2 * 10^5 \left[2.07 * \left(\frac{V_1^2 I_K^2}{K} \right) \right] \quad (9)$$

Differentiating the filter cost (C_F) with respect to the filter size (S_K) and equating to zero; the minimum value of the filter size (S_{KMIN}) and its corresponding filter arm's cost(C_{FMIN}) will be given as:

$$S_{KMIN} = \sqrt{\frac{B}{A}} \quad (10)$$

$$C_{FMIN} = 2\sqrt{A * B} \quad (11)$$

Finally, the economical value of the parameters of the suggested harmonic filter will be given as

$$C_K = \frac{S_{KMIN}}{\omega a_K V_1^2} \quad (12)$$

$$L_K = \frac{1}{\omega_K^2 C_K} \quad (13)$$

where: ω is the fundamental angular frequency in radians and ω_K is the angular frequency at harmonic order K in radians.

III. Reactive Power Constraint

The economic method presented is an effective manner if the amount of the reactive power needed to be supplied by filters is adequate. However, if it is not, installing an additional shunt capacitor will be suitable to make the sufficient coherence between the economic values of the reactive power and the value required [7].

In other words, multiple-arm harmonic passive filter is used for filtering specific harmonic orders, in addition to a high-pass filter for higher harmonic orders. However, this solution has the disadvantage of high ohmic losses in the high-pass circuit, and thus it is more economically to attach directly shunt capacitor (C_D) to the bus under consideration in parallel with the proposed multiple-arms of the harmonic passive filter, because of the lower losses expected [5]. In the same time, this capacitor compensates the rest of the required reactive power as the reactive powers supplied by the capacitors of the filter multiple-arms are limited to their economic values. Thus, the reactive power needed to be supplied by the shunt capacitor (S_{SH}) is given as

$$S_{SH} = S_{REQ} - \sum_{i=1}^{N} S_{iMIN} \tag{14}$$

where, S_{REQ} is the total reactive power required for power factor correction and N is the number of filter arms and (S_{iMIN}) is the economical value of each filter arm. Thus, the shunt capacitor value, and its cost (C_{SH}) including its energy losses cost can be calculated as follows:

$$C_{SH} = \left[U_C + 7274.3\right] S_{SH} \tag{15}$$

Hence, the complete expression of the harmonic passive filter total cost (TCOST) including the direct shunt capacitor cost (if needed) will be given as

$$C_D = \frac{S_{SH}}{\omega V_1^2} \tag{16}$$

$$TCOST_{MIN} = 2\sqrt{A*B} + \left[U_C + 7274.3\right] S_{SH} \tag{17}$$

IV. Case Studies

Two numerical case studies have been introduced to show the effect of different voltage levels on the system performance, for two different systems' short-circuit capacities considering various load distortion percents, as follows:

A. Case study :

This case study is a practical case study for a factory within the industrial zone of sixth October City, Giza, Egypt. The measurements were carried out on the low voltage side of transformer 20/0.66 kV, 1 MVA [5]. The results of the measurements of current harmonics are shown Table I. The supply bus voltage is 0.66 kV (380 volt line-to-neutral). The system data for equivalent single-phase mode is:

Maximum current (I_{MAX}) = 420 in amperes.
Short circuit current (I_{SC}) = 30 kA.
Total harmonic distortion (*THD*) =37.6 in percent.
I_{SC} / I_{MAX} = 71.4.
Power factor before correction = 76 in percent.
Power factor required after correction = 95 in percent.

TABLE I
CURRENT HARMONICS MEASUREMENTS FOR THE INDUSTRIAL PLANT: CASE STUDY1

Harmonic Order	% of fundamental	Standard percent
5	33.34	10
7	14.28	10
11	9.50	4.5
13	2.85	4.5

As shown in Table I, tests employing a power quality analyzer show that some harmonics do exist in the power system network and exceed the standard IEEE limits [12]. Therefore, it is proposed to install three passive filter arms (fifth, seventh and eleventh) for harmonic suppression, while improving the load power factor to a desired specific value (95%).

Analyzing the system data, the following parameters can be simply calculated and organized as follows:

Power factor required after correction = 0.95.
The required three phase reactive power = 0.192 Mvar.
The required reactive power per phase = 0.064 Mvar.
From equal capacitance technique, the filter consists of three arms, and the required reactive power per phase per arm = 0.0213 Mvar.

Table II shows the system results for the demonstrated capacitance division strategies. Comparison of the results given in Table II shows that the proposed methods are acceptable, providing an efficient system performance compared with the traditional equal capacitance method. This validates the practical observation that a better performance is usually obtained with unequal capacitor sizes in the multiple-arm. Supplementary calculation for the shunt capacitance directly connected to the bus is summarized in Table III.

TABLE II
SIMULATION RESULTS

Harmonics Order	Parameters	Equal capacitance method	Optimal capacitance method
5	S_5(Mvar)	0.0213	0.0325
	C_5 (µF)	467.60	880.81
	L_5 (mH)	0.87	0.46
	A_5 (L.E./Mvar)	115910.73	
	B_5 (L.E./Mvar)	122.86	
	C_{F5} (L.E.)	8231.87	7547.39
7	S_7(Mvar)	0.0213	0.0119
	C_7 (µF)	467.60	255.4644
	L_7 (mH)	0.4419	0.8088
	A_7 (L.E./Mvar)	111592.52	
	B_7 (L.E./Mvar)	15.80	
	C_{F7} (L.E.)	3121.07	2655.37
11	S_{11}(Mvar)	0.0213	0.0063
	C_{11} (µF)	467.60	138.31
	L_{11} (mH)	0.18	0.60
	A_{11} (L.E./Mvar)	109001.69	
	B_{11} (L.E./Mvar)	4.41	
	C_{F11} (L.E.)	2532.19	1387.11

TABLE III
SIMULATION RESULTS FOR THE SHUNT CAPACITOR: CASE 1

Parameters	Optimal capacitance method, case1
S_{SH} (Mvar)	0.0132
C_D (μF)	84.58
C_{SH} (L.E.)	1411.82

It is obvious that the cost of each filter arm in the optimal capacitance method is much lower than that in the equal capacitance method. Fig. 1 shows a total cost (*TCOST*) comparison for the installed passive filter components.

Fig. 2 shows the variations of the passive filter multiple-arm's cost with the arm size.

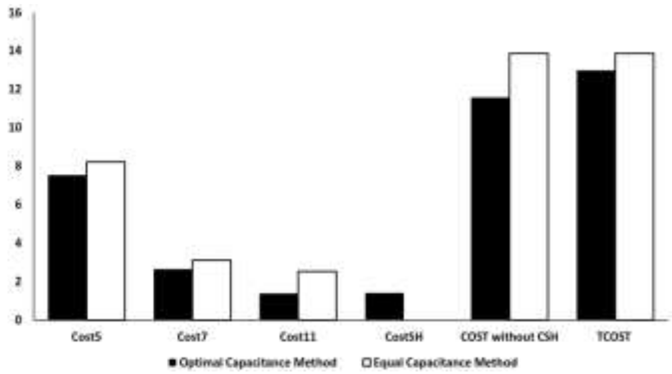
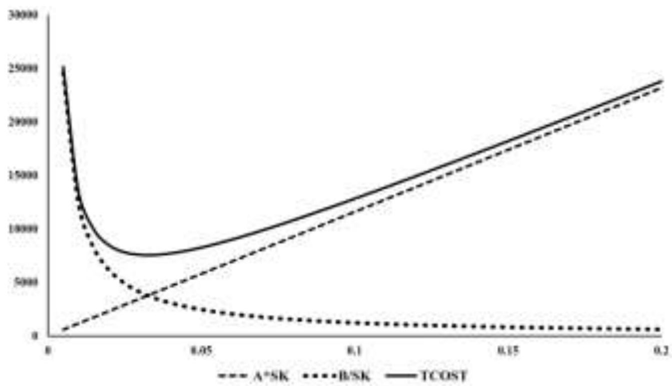
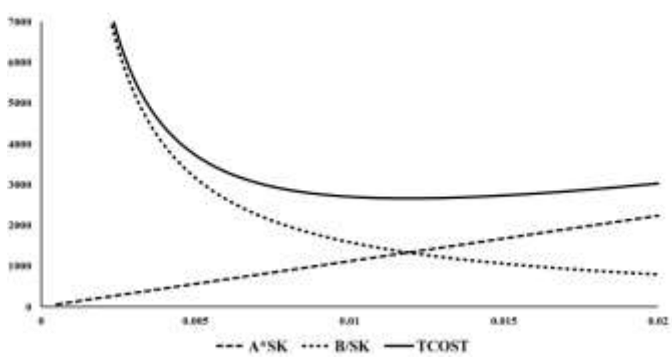


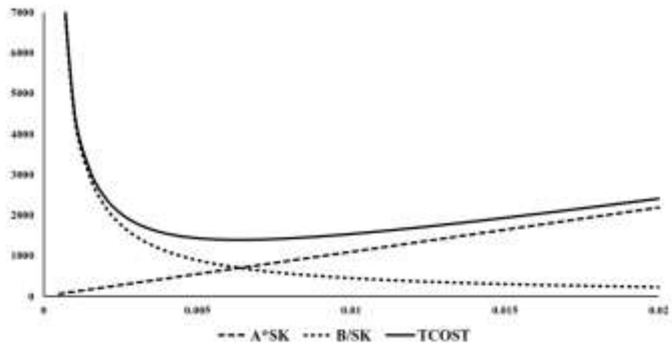
Fig.1. Total cost comparison for the installed passive filter multiple-arm



(a) Fifth



(b) Seventh



(c) Thirteenth

Fig.2. Variations of passive filter multiple-arm's cost with the arm size

Regarding summation of the supplied reactive shown in Table II; it is obvious that their summation per phase in megavars equals to 0.0508, which is lower than the reactive power required for improving the power factor to 95%, which means that the corrected power factor will be approximately 92%. Therefore, a deep view must be approved before deciding usage of additional shunt capacitor.

No attempt has been made so far to analyze the impact of loads distortion percents on passive harmonic filter banks design in industrial applications. Fig. 4 shows the effect of changing total harmonic distortion percent on the expected total cost. Results for lower total harmonic distortion percents systems indicate the following:

If the percentage of load distortion is low (varies from two to three times the allowable standard percentage), the equal capacitance technique will be the most appropriate scenario; if it is higher (more than three times the allowable standard percentage), then the economical method is the best [7].

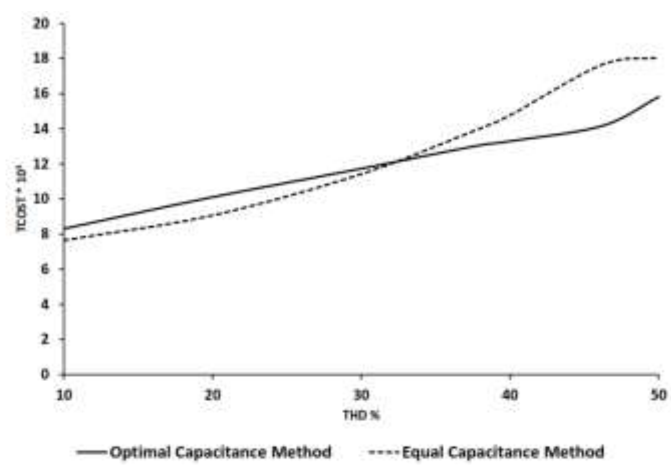


Fig.3. Impact of total harmonic distortion on the cost of the installed passive filter multiple-arm, case 1

B. *Case study 2:*

Data from industrial plant data were taken from an example in IEEE publications [12], where the inductive three-phase loads are 6400 kW and 4905 kVAR. The 60-cycle supply bus voltage is 4.16 kV (2400 volt line-to-neutral), 80 MVA short circuit capacity. The results of the measurements of current harmonics are shown Table IV.

The system data for equivalent single-phase mode are:
Total harmonic distortion (*THD*) =25.01 in percent.
Frequency = 60 Hertz
Maximum current (I_{MAX}) = 988 in amperes.
Short circuit capacity (MVA_{SC}) = 26.67 MVA.
MVA_{SC} / MVA_L = 11.24.
Power factor (PF) before correction = 79%.
Power factor required after correction = 95%.

TABLE IV
CURRENT HARMONICS DISTORTION FOR THE INDUSTRIAL PLANT UNDER STUDY: CASE 2

Harmonic Order	% of fundamental	Standard percent
3	20.95	4
5	11.54	4
7	6.27	4
11	3.75	2

As shown in Table IV, it is proposed to install four passive filter arms (third, fifth, seventh and eleventh) for harmonic suppression, while improving the load power factor to a desired specific value.

Analyzing the system data, the following parameters can be easily calculated and arranged as follows:

Power factor required after correction = 0.95%.
The required three phase reactive power = 2.40 Mvar.
The required reactive power per phase = 0.8 Mvar.

From the equal capacitance technique, the filter consists of four arms, and the required reactive power per phase per arm = 0.2 Mvar.

Table V shows the system results. It is obvious that the cost of each filter arm in optimal capacitance method is still much lower than that in the conventional equal capacitance method.

Also, it is obvious that the total filter size per phase equals to 0.66 Mvar, which is lower than the reactive power required for improving the power factor to 95%, which means that the corrected power factor will be approximately 93%. Supplementary calculations for the shunt capacitance directly connected to the bus are summarized in Table VI.

TABLE V
SIMULATION RESULTS: CASE2

Harmonics Order	Parameters	Equal capacitance method	Optimal capacitance method
3	S_3(Mvar)	0.1998	0.3795
	C_3 (μF)	91.98	155.30
	L_3 (mH)	8.49	5.03
	A_3 (L.E./Mvar)	133183.6	
	B_3 (L.E./Mvar)	19184.03	
	C_{F3} (10^3*L.E.)	122.62	101.09
5	S_5(Mvar)	0.1998	0.1669
	C_5 (μF)	91.98	73.80
	L_5 (mH)	3.06	3.81
	A_5 (L.E./Mvar)	115910.7	
	B_5 (L.E./Mvar)	3232.48	
	C_{F5} (10^3*L.E.)	39.33	38.71
7	S_7(Mvar)	0.1998	0.0774
	C_7 (μF)	91.98	34.92
	L_7 (mH)	1.56	4.11
	A_7 (L.E./Mvar)	111592.5	
	B_7 (L.E./Mvar)	669.28	
	C_{F7} (10^3*L.E.)	25.64	17.28
11	S_{11}(Mvar)	0.1998	0.371
	C_{11} (μF)	91.98	16.93
	L_{11} (mH)	0.63	3.43
	A_{11} (L.E./Mvar)	109001.6	
	B_{11} (L.E./Mvar)	149.82	
	C_{F11} (10^3*L.E.)	22.52	8.08

TABLE VI
SIMULATION RESULTS FOR THE SHUNT CAPACITOR: CASE2

Parameters	Optimal capacitance method, case2
S_{SH} (Mvar)	0.1381
C_D (μF)	63.60
C_{SH} (10^3*L.E.)	14.82

Fig. 4 shows a total cost (*TCOST*) comparison for the installed passive filter components. Even with reactive power limitation to their economical values, and the necessity of the directly connected capacitor; the total cost based on optimal capacitance method is still much lower than that in the equal capacitance method.

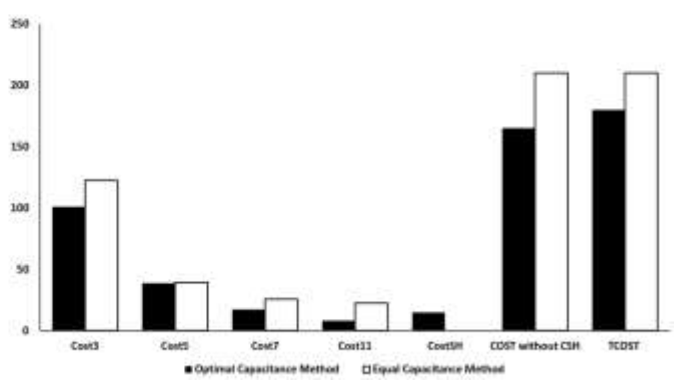


Fig.4. Total cost comparison for the installed passive filter multiple-arm

Fig. 5 shows the impact of changing total harmonic distortion percent on the expected total cost.

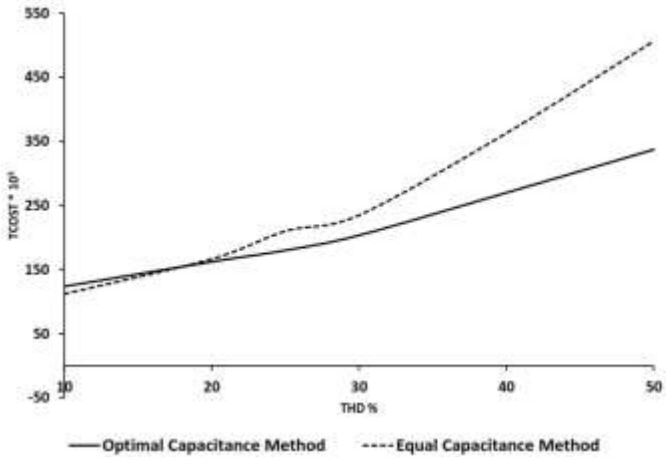


Fig.5. Impact of total harmonic distortion on the cost of the installed passive filter multiple-arm, case 2

From the system results and the knowledge gained from this study, it is noted, for lower short-circuit capacity systems, lower *THD* standard limits, that the proposed economical method is much better than the conventional method because of its effectiveness and fast convergence to the technical and economical solution in the choice of relative size of capacitor values of multiple-arm passive harmonic filters. Also, a crucial proxy to the multiple-arm passive harmonic filters design is not to pre-determine a desired specific value of corrected load power factor, but to obtain a good compromise solution and save your cash [13], [14].

V. CONCLUSION

There are different methods for dividing the total capacitance of multiple-arm harmonic passive filters in industrial use. Economical topology that enable appropriate calculations for capacitor bank division among multiple-arm shunt passive filters is tested by means of two numerical case studies, and the general procedure of the method used is acceptable compared to the conventional equal capacitance method. It has been validated that the proposed harmonic filter with optimal capacitance method is more economical for large distorted loads than that designed on equal capacitance method.

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