OPTIMAL HARMONIC PASSIVE FILTERS FOR POWER FACTOR CORRECTION, HARMONIC MITIGATION AND ELECTRICITY BILL REDUCTION USING DRAGONFLY ALGORITHM

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ABSTRACT

One of the common techniques for harmonics mitigation in heavy industrial applications is the use of C-type passive filters. Besides, their applicability in power distribution systems is growing. Although single-tuned passive filters are more dominant in industrial applications, their usage is declining in front of C-type filters, particularly from the perspective of utilities or operators. The main reasons are the resonance damping capabilities offered by the C-type filters and the reduced voltage distortion and power losses they can guarantee. In this paper, an optimal design of C–type filter is presented based on maximization of the total saved cash to recoup the filter investment funds to reduce the annual electricity bill, improve the power factor and mitigate harmonic distortion in distribution systems supplying nonlinear loads. A recent swarming search algorithm based on the behavior of dragonflies, known as Dragonfly Algorithm is used for solving the problem. The economic assessment is based on the latest Egyptian energy tariff. The results show that the proposed filter considerably enhances the power quality performance of the system and reduces the annual electricity bill.

INTRODUCTION

Power quality (PQ) is a technical evaluation of the performance level of an electrical system using suitable indices to retain equipment operation in a planned manner without additional losses. In this regard, high penetration of distributed generation (DG) resources in power systems with their power-electronic interfaces and the proliferation of nonlinear loads have led to different PQ problems for both consumers and utilities [1].

Harmonic distortion is one of the significant PQ issues because of its adverse impacts on utilities and electricity users [2]. Many works pointed out that harmonically distorted voltages and currents may have adverse effects on power system equipment as overheating, increase of losses, failure of capacitor banks, nuisance tripping of relays and interference to communication systems [3]. Hence, to stay competitive in today's deregulated electricity markets; utilities, consumers and prosumers (a recently-developed term which defines the electrical user that consumes and produces electricity) are facing new challenges in providing better supply quality and reliability. Accordingly, consumers who suffer from low power factor (*PF*) values and technical problems caused by the ineffective use of their equipment under non-sinusoidal conditions should use *PF* improvement and harmonic distortion mitigation techniques to save the wasted energy and cash. In this regard, several solutions have been practiced for maintaining a harmonically free power grid. Both passive and active filters have been employed to limit the voltage and current harmonic distortion. Active filters provide good performance for harmonic suppression. However, they are expensive and more complex compared to passive filters, this is why they are commercially available in low-voltage applications. In the broadest scene, shunt passive filters are the most used filters in practice for harmonic mitigation and reactive power compensation [3], [4].

Shunt passive filters have various configurations. The most popular configuration is the single-tuned that can provide adequate harmonic mitigation capability but may suffer from resonance hazards. High-pass filters come second in the industrial applications for reducing multiple high-order harmonic frequencies. A high-pass filter has relatively weaker harmonic mitigation capability compared to a tuned filter, but they do not suffer from harmonic resonance hazards. Among them, *C*-type passive filter is an alternative scheme of the 3rd order high-pass that guarantees proper harmonic mitigation for a wide range of harmonics, eliminates resonance risks, and has a considerable low power loss compared to other passive filter types as it acts as a shunt capacitor bank at the fundamental frequency [3], [5].

In this paper, an optimal design of a *C*–type filter is presented. The optimal size of its parameters is found using a recent meta-heuristic search algorithm based on the behavior of dragonflies, called Dragonfly Algorithm (DA), to maximize the total saved cash due to *PF* correction, harmonic mitigation, and energy saving. Individual and total harmonic distortion limits of the voltage at the point of common coupling (PCC), transmission power loss, and power factor are considered the criteria that evaluate the performance of the system before and after compensation. Further, appraisal of the economic merits of the filter to reduce the annual electricity bill is presented. The economic assessment is based on the recent Egyptian energy tariff [6], [7]. DA was used because of its computational efficiency and fast convergence to the global solution with acceptable accuracy [8].

DESIGN OF THE *C*-TYPE FILTER

The equivalent circuit of a single-phase *C*-type filter is shown in Fig. 1. This configuration comprises of two capacitors, namely the main capacitor C_{F1} that is responsible for reactive power compensation and the auxiliary capacitor C_{F2} that is sized to allow the equality of its capacitive reactance and the inductive reactance (jX_{LF}) offered by the filter's inductance L_F at the fundamental frequency (f_1), to bypass the parallel resistor R_F and thus minimizing the fundamental power loss [9], [10]. For this reason, the *C*-type passive filter is considered an energy efficient passive filter. The *h*th harmonic impedance Z_{Ch} of the *C*-type filter, its real component (R_{Ch}) and imaginary component (X_{Ch}) are expressed below, where *h* is the harmonic order.

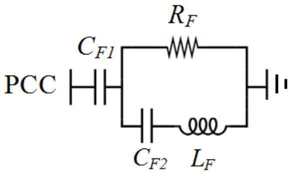

Fig. 1 The equivalent circuit of the *C*-type filter

$$Z_{Ch} = R_{Ch} + jX_{Ch} \tag{1}$$

$$R_{Ch} = \frac{R_F\left(hX_{LF} - \dfrac{X_{CF2}}{h}\right)^2}{R_F^2 + \left(hX_{LF} - \dfrac{X_{CF2}}{h}\right)^2} \tag{2}$$

$$X_{Ch} = j\left(\frac{R_F^2\left(hX_{LF} - \dfrac{X_{CF2}}{h}\right)}{R_F^2 + \left(hX_{LF} - \dfrac{X_{CF2}}{h}\right)^2} - \frac{X_{CF1}}{h}\right) \tag{3}$$

At f_1, the *C*–type filter acts as a capacitor C_{F1} that provide the system with a reactive power ($Q_{desired}$) to correct the displacement power factor to its acceptable value, thus:

$$X_{CF1} = \frac{V_{rated}^2}{Q_{desired}} \tag{4}$$

where V_{rated} is the nominal system voltage. Also, at f_1, X_{CF2} and X_{LF} are equal. Further, as frequency increases, X_{CF2}/h decreases, whilst the hX_{LF} increases. Therefore, the inductive impedance calculated by their series connection will dominate. At this stage, the filter acts in a similar manner to a second-order filter. At the tuning harmonic order (h_t), the equivalent inductive reactance of the filter resonates with the equivalent capacitive reactance, thus:

$$R_F = \frac{h_t^2 - 1}{h_t\sqrt{\left(\dfrac{h_t^2-1}{X_{CF1}\times X_{CF2}}\right) - \dfrac{1}{\left(X_{CF2}\right)^2}}} \tag{5}$$

At higher frequencies, the inductive reactance will considerably increase with the harmonic frequency. Accordingly, most of the current will flow through the main capacitor and the resistive branch. However, one has to make sure that the filter equivalent impedance should be inductive above the tuning frequency [10]; this leads to (6), thus:

$$\left(\frac{h^2-1}{h^2}\right)C_{F1} \le C_{F2} < \left(h^2-1\right)C_{F1} \tag{6}$$

WORKING EXAMPLE

The distribution system given in Fig. 2 is considered in this study and it was originally presented in IEEE 519-1992 [11]. The nonlinear loads are considered to be supplied from a distorted utility supply. The proposed filter connects to the system at the PCC [12], [13]. In this work, the current-source model is used to represent the harmonic currents generated by the nonlinear loads, where I_h represents the harmonic currents. The linear loads and the group of induction motors are represented by their equivalent impedance Z_{Lh} at *h* so that $Z_{Lh} = R_{Lh} + jhX_{L1}$. The fundamental load resistance R_{L1} and reactance X_{L1} are calculated using the fundamental load active and reactive powers. The utility is represented by its Thevenin equivalent in terms of the background supply voltage V_{Sh} and the Thevenin impedance Z_{Sh}, so that $Z_{Sh}=R_{Sh}+jhX_{S1}$. Background harmonic voltage V_{Sh} is given in percentages of the fundamental voltage. The *h*th harmonic PCC voltage is denoted by V_{Lh}, and the supply current is denoted by I_{Sh}. Using circuit analysis, I_{Sh} is given as follows:

$$I_{Sh} = \frac{V_{Sh}}{\left(Z_{Sh} + \dfrac{Z_{Lh}Z_{Ch}}{Z_{Lh}+Z_{Ch}}\right)} + \frac{I_h Z_{Lh} Z_{Ch}}{\left(Z_{Sh}\left(Z_{Lh}+Z_{Ch}\right) + Z_{Lh}Z_{Ch}\right)} \tag{7}$$

Also, V_{Lh} is expressed as

$$V_{Lh} = V_{Sh} - Z_{Sh} I_{Sh} \tag{8}$$

The considered PQ assessment criteria are the total demand distortion (*TDD*), total harmonic voltage distortion (THD_v), individual harmonic voltage distortion (IHD_v), *PF*, power loss (ΔP_{loss}) and the displacement power factor (*DPF*). They can be expressed, respectively, as follows:

$$TDD(\%) = 100 \times \frac{\sqrt{\sum_{h>1}\left|I_L^h\right|^2}}{I_{fl}} \tag{9}$$

$$THD_v(\%) = 100 \times \frac{\sqrt{\sum_{h>1}\left|V_L^h\right|^2}}{V_{L1}} \tag{10}$$

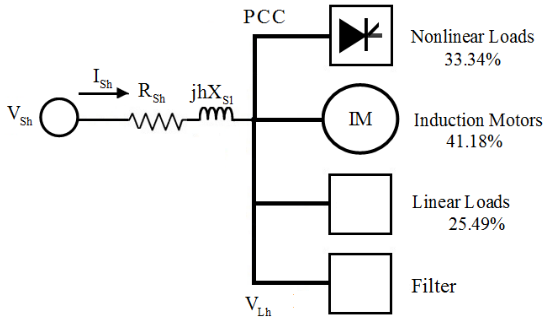

Fig. 2 The test system under study

$$IHD_v(\%) = 100 \times \frac{V_{Lh}}{V_{L1}} \tag{11}$$

$$PF = \frac{\sum_h V_{Lh} I_{Sh} \cos(\phi_h)}{\sqrt{\sum_h V_{Lh}^2}\sqrt{\sum_h I_{Sh}^2}} \tag{12}$$

$$\Delta P_{loss} = \sum_h I_{Sh}^2 R_{Sh} \tag{13}$$

$$DPF = \cos(\phi_1) \tag{14}$$

where ϕ_h denotes the hth harmonic phase angle between V_{Lh} and I_{Sh}, and ϕ_1 is its fundamental value. I_{fl} represents the system's maximum demand current.

ECONOMIC INDICES

The filter's total cost (*TC*) is given as follows:

$$TC = U_C(Q_{C1} + Q_{C2}) + U_L Q_L + C_E \tag{15}$$

where U_C and U_L are unit costs of the capacitor and the inductor in Egyptian pounds per kilovar (L.E./kvar), so that U_C=70 L.E./kvar and U_L=85 L.E./kvar. Q_{C1}, Q_{C2} and Q_L are ratings of the main capacitor, auxiliary capacitor and inductor, respectively. C_E is the cost of the energy losses and is expressed in terms of the equivalent capital cost by use of the present value factor P_V given below.

$$P_V = \frac{(1+i)^y - 1}{i(1+i)^y} \tag{16}$$

where i is the interest rate (i=8%) and y is the filter lifetime in years, which is assumed to be 10 years [10]. Accordingly, C_E is given as:

$$C_E = (T \times P_V \times F_V \times b)\Delta P_f \tag{17}$$

where b is the consumed energy charge rate that is equal to 0.767 L.E. per kWh [6]. F_V is the filter utilization factor which is set to 1 [12]. T is the number of operating hours per year (T=8760 hours/year). ΔP_f is the filter's active power loss.
To ensure an efficient utilization of electrical energy, electricity companies impose an oblige charge for low power factors, so-called as PF penalty. According to the Egyptian tariff [6], [7], it comprises 0.5% increase of the total consumed energy for every 1% below a *PF* of 92%. Also, it comprises 1% increase of the total consumed energy for every 1% below a *PF* of 72%. Conversely, a bonus (discount) of 0.5% from the total consumed energy for every 1% above a *PF* of 92% up to 95% is guaranteed to consumers to retain their average *PF* in this desired range. Furthermore, it should be mentioned that increasing *PF* may permit reduction of consumers' contracted power (demand charge reduction). Thus, cash saved due to *PF* correction is expressed as: (saved cash = negated penalty + granted discount + saved cash due to reduced energy consumption charges + contracted demand charge reduction) as explained in [13]. Hence, the annual electricity bill (*AEB*) is formulated as follows:

$$AEB = a(P_{demand}) + b(E_{consumed}) + penalty - bonus \tag{18}$$

where a is the demand charge rate that is set to 50 L.E./kW/month. P_{demand} is the contracted demand power (kW). $E_{consumed}$ is the total annual energy consumed (kWh). So, we can calculate the annual money saved (*Sav*) as the difference between the old annual electricity bill (*OB*) and the new annual electricity bill (*NB*), thus:

$$OB = a(P_{demand,\,old}) + b(E_{consumed,\,old}) + penalty - bonus$$

$$NB = a(P_{demand,\,new}) + b(E_{consumed,\,new}) + penalty - bonus$$
$$Sav = OB - NB \tag{19}$$

The payback period (*PP*) is a time period in years needed for the income (or saving) to equal the investment cost (*TC*). It is formulated as the ratio between *TC* and *Sav* [14], *i.e. PP=TC/Sav*

THE OPTIMIZATION PROBLEM

Maximization of *Sav* is proposed as an objective function (OF) in the optimization problem, as follows:

$$OF = \text{Maximize}\; Sav(X_{CF1}, X_{CF2}, X_{LF}, R_F) \tag{20}$$

Subjected to

$$\begin{aligned}
&0.92 \le DPF(X_{CF1}, X_{CF2}, X_{LF}, R_F) \le 1.00,\\
&0.92 \le PF(X_{CF1}, X_{CF2}, X_{LF}, R_F) \le 1.00,\\
&THD_v(X_{CF1}, X_{CF2}, X_{LF}, R_F) \le 5.00\%,\\
&IHD_v(X_{CF1}, X_{CF2}, X_{LF}, R_F) \le 3.00\%,\\
&V_L^{\min} \le V_L(X_{CF1}, X_{CF2}, X_{LF}, R_F) \le V_L^{\max},\\
&TDD(X_{CF1}, X_{CF2}, X_{LF}, R_F) \le 8.00\%.
\end{aligned} \tag{21}$$

V_L^{min} and V_L^{max} are the minimum and maximum rms voltages values, and they are given as 0.95V_L and 1.05V_L, respectively.

SEARCH ALGORITHM

Nature-inspired optimization algorithms have the ability to avoid local optima stagnation. In this work, DA is used to solve the optimal filter design problem. The DA mimics the behavior of dragonflies in their static and dynamic swarming in food-searching activities, hiding from enemies and migration journeys [8]. The main DA control parameters are mathematically modeled follows:

The separation of the ith element (S_i):

$$S_i = -\sum_{i=1}^{M} X - X_i \tag{22}$$

where X is the position of the current individual, X_i shows the position ith neighboring individual, and M is the number of neighbor dragonflies.

The orientation of the ith element (O_i):

$$O_i = \frac{\sum_{i=1}^{M} V_i}{M} \tag{23}$$

where V_i shows the velocity of the ith element.

The cohesion of the ith element (C_i):

$$C_i = \frac{\sum_{i=1}^{M} X_i}{M} - X \tag{24}$$

The attraction of the ith element (W_i):

$$W_i = X^{best} - X \tag{25}$$

where X^{best} denotes the location of the food source.

The diversion of the ith element (D_i):

$$D_i = X^{enemy} - X \tag{26}$$

where X^{enemy} represents the location of the enemy.

Accordingly, updating the position of the dragonfly can be performed as follows:

$$X_{i+1} = X_i + \Delta X = X_i + \left(l_1 S_i + l_2 O_i + l_3 C_i + l_4 W_i + l_5 D_i\right) \tag{27}$$

where l_1, l_2, l_3, l_4, l_5 are weighting factors for the separation, orientation, cohesion, attraction and diversion, respectively. They are set to 0.35, 0.1, 0.1, 0.7, 1, and 1, respectively. The maximum number of iterations is set to 500 and the number of dragonflies per swarm is set to 40. Fig. 3 presents a flowchart of the proposed DA.

RESULTS AND DISCUSSIONS

In the working system given in Fig. 2, the nominal system line-voltage is 4.16 kV, f_1 is 50 Hz, and the three-phase short-circuit level (SCL) is 80 MVA. Table 1 shows the single-phase system data. Table 2 shows the harmonic signature for the background voltage and the nonlinear load currents. For the uncompensated system, *DPF*, *PF*, *TDD*, THD_v percentages are 71.65, 71.36, 5.1271and 6.335, respectively. The single-phase transmission power loss is 18.5681. It is noticed that the THD_v percentage exceeds the IEEE 519 limit.

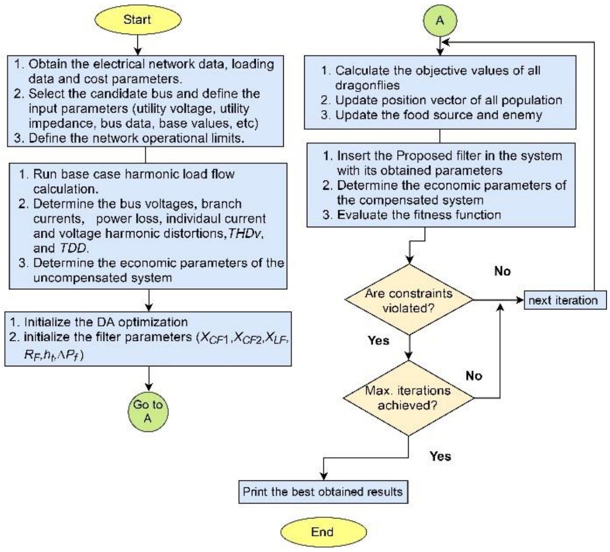

Fig. 3 Flowchart of the proposed search algorithm

Table 1. The studied system data

Parameter	*Value*	*Parameter*	*Value*
SCL (MVA)	26.667	X_{S1} (Ω)	0.2163
V_L (kV)	2.4	P_1 (kW)	1700
f_1 (Hz)	50	Q_1 (kvar)	1650
I_{fl} (A)	1000	R_{L1} (Ω)	1.742
R_{S1} (Ω)	0.0216	X_{L1} (Ω)	1.696

Table 2. Voltage and current harmonics data

h	V_{Sh} *(V)*	I_h *(A)*	*h*	V_{Sh} *(V)*	I_h *(A)*
5	48.00	25.68	17	13.20	1.98
7	36.00	15.81	19	4.80	0.99
11	21.60	34.57	23	3.60	8.89
13	16.80	28.65	25	2.40	7.90

Table 3 shows the results of the optimized parameters of the proposed filter.

Table 3. Values of the filter parameters

Parameter	*Value*	*Parameter*	*Value*
X_{CF1} (Ω)	5.26212	R_F (Ω)	6.1511
X_{CF2} (Ω)	1.2709	h_t	2.4189
X_{LF} (Ω)	1.2709	ΔP_f (kW)	2.5150

Table 4 shows the technical and economic performance indices of both the uncompensated and compensated systems, respectively. The proposed filter efficiently improves both the *DPF* and *PF* to their acceptable values, as well as reducing ΔP_{loss} by 38.67%, while enhancing the PCC voltage to its acceptable value within the bounds. Besides, it is obvious that the *TDD* and THD_v values are decreased to comply with the IEEE 519 limit. Also, Fig. 4 shows that the IHD_v values of the compensated system meet the IEEE 519 standard limits.

Table 4. Technical and economic criteria

Parameter	*Uncompensated system*	*Compensated system*
I_S (A)	923.750	723.843
V_L (kV)	2.248	2.345
V_L (%)	93.65	97.71
PF (%)	71.36	94.999
DPF (%)	71.65	95.103
ΔP_{loss} (kW)	18.5681	11.388
TDD (%)	5.1271	3.849
THD_v (%)	6.3355	3.294
TC (10^3 L.E.)	---	302.269
Penalty (10^6 L.E./year)	3.1783	0.000
Bonus (10^3 L.E./year)	0.0000	485.127
AEP (10^6 L.E./year)	36.0998	34.751
Sav (10^6 L.E./year)	0.0000	1.349
PP (years)	---	0.672

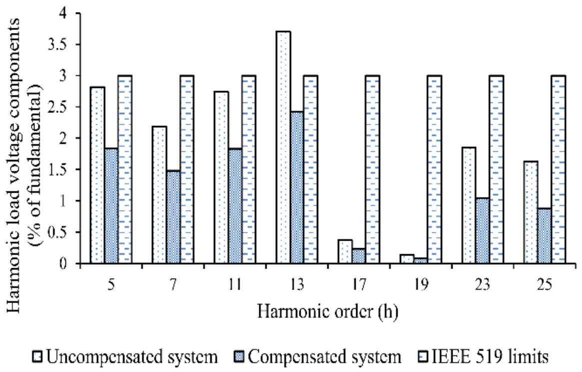

Fig. 4 Harmonic content of the PCC voltage before and after compensation.

Furthermore, based on the Egyptian tariff, we noticed that *PF* correction and harmonic mitigation play an efficient role in enhancing PQ performance of the system, but marginally reduce the annual electricity bill (almost 3.7%) which is an acceptable percent in practice.

CONCLUSIONS

Passive filters are used to mitigate harmonics problem in all industrial sectors; however the decision to apply one harmonic solution rather than another is almost always related to economic considerations. In this paper, an optimal design of *C*–type filter is presented using DA. It was obvious that filter can mitigate harmonics effectively, with a low filtering cost that is mainly because of its low active power losses. Besides, assessment of the economic merits of the filter to lower the electricity bill of a distribution system supplying nonlinear loads is discussed. It is concluded that the filter succeeded in reducing the annual electricity bill by almost 3.7%, which meets the representative bill reduction range worldwide (between 1 and 4%). In addition, it was evident that the *PP* with passive filters is, in general, less than one year.

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