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Practical considerations for reactive power sharing approaches among multiple-arm passive filters in non-sinusoidal power systems

Ziad M. Ali[a,b], Faisal Q. Alenezi[c], Sameh S. Kandil[d], Shady H.E. Abdel Aleem[e,*]

[a] Electrical Engineering Department, College of Engineering at Wadi Addawaser, 11991, Prince Sattam bin Abdulaziz University, Saudi Arabia
[b] Electrical Engineering Department, Aswan faculty of Engineering, 81542, Aswan University, Egypt
[c] College of Technological Studies, PAAET, Kuwait
[d] Senior Engineer, PSP El-Sewedy Company, New Cairo, Egypt
[e] Higher Institute of Engineering, Mathematical and Physical Sciences, 15th of May, Cairo, Egypt

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ABSTRACT

Shunt passive filters are considered as the most reliable and economical tool for power factor improvement and harmonic suppression. Many mathematical techniques have been developed in the literature for reactive power division among multiple passive filter arms, taking into consideration different techno-economic aspects. In this paper, firstly, a comprehensive overview of all reactive power-sharing approaches among multiple-arm passive filters was presented. The eight presented approaches cover all of the former and recent industrial and research methods. Secondly, this article presented a new method of multiple-arm passive filter design based on the crow search algorithm (CSA) to minimize the total harmonic current distortion (THDI) as an objective function for an industrial plant. The simulated system was modeled through Matlab and the results are compared with eight conventional techniques with respect to the technical aspects such as filter efficiency, harmonic distortion levels, filter failure, interaction with the system, and filter cost to determine the most efficient design technique. Simulations are carried out in ETAP and Matlab environments. The simulation results obtained show the disadvantages of the traditional design methods and the advantage of the proposed solution among the other methods.

1. Introduction

Power quality studies have been given much attention during the last decades, focusing on the main issues that cause harmful effects on power system networks such as voltage sag and swell, impulsive and oscillatory transients, over- and under-voltages, frequency deviations, and voltage flicker. Inverters, the main core of modern renewable energy systems such as solar and wind power plants, electronic devices, adjustable speed drives (ASD), switching devices, lighting emitting diodes (LED) discharge lamps, and arcing equipment, lead to a dramatic rise in the non-sinusoidal currents injected into the power grid, which are known as harmonics [1–7].

On one hand, power system harmonics may cause overloading and overheating of different types of equipment such as transformers, motors, cables, and transmission lines, decreasing their lifetime and efficiency [5–8]. In addition, they may lead to malfunctioning of the protective equipment. On the other hand, series and parallel resonance caused at some harmonic frequencies may result in amplified currents and voltages, which may have harmful effects on essential and expensive equipment [8–11].

Shunt passive filters are widely used to mitigate one or more harmonic frequencies. Their simple construction, reliable operation, and cheapness have made them one of the most frequently applied solutions for power factor correction and harmonic mitigation in industrial applications [11,12]. Also, shunt passive filters can be used to mitigate harmonic frequencies as presented in [5,7] to overcome overloading and overheating of equipment that operate in non-sinusoidal systems.

Various design methods have been used for reactive power division among the filter arms such as minimum cost, equal capacitance, equal inductance, equal specific losses, minimum capacitor rating, and mutual frequency influence approaches.

In [13], four methods of multiple-arm passive-filter design, namely equal capacitance, equal inductance, equal specific losses, and minimum capacitor rating, have been compared with respect to their cost and effectiveness. The research concludes that better performance can be achieved with unequal division of reactive power among the filter arms compared to equal division.

In [14], four approaches for passive filter design were compared. Two approaches were based on the inverse relation between the

* Corresponding author.
E-mail address: engyshady@ieee.org (S.H.E. Abdel Aleem).

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reactive power required for compensation and for the harmonic order to be eliminated. The other two approaches were based on equal capacitance and impedance-frequency relation. The comparison focused on the technical sides such as power losses and harmonic distortion levels without paying any attention to the filter cost.

In [15], a comparative study of different design techniques for the passive filter design was performed, considering technical aspects such as harmonic distortion levels, filter effectiveness, harmonic amplification ratio, and filter outage effect. Moreover, the filter cost was analyzed to decide the most economical technique. However, none of the above attempts selected the most efficient and reliable method of passive filter design to put into practice. As far as known, most design methods depend on the designer's experience, and they do not guarantee compliance with the permissible international standards limits. Consequently, in most cases, an optimal filter design method is needed.

Modern meta-heuristic optimization algorithms such as the genetic algorithm, particle swarm optimization, group search optimization, simulated annealing, and other techniques are used to meet design restrictions and offer promising results regarding the passive filter design problem by obtaining optimal solutions [16,17].

This research, first, introduces a comprehensive overview of all reactive power-sharing approaches among multiple-arm passive filters available in the literature, namely equal capacitance, fixed step, harmonic content, equal inductance, equal capacitor losses, minimum capacitor rating, mutual frequency influence, and cost minimization. Second, it introduces a new solution for the optimal design problem of multiple-arm shunt passive filters using a recent nature-inspired technique known as the crow search algorithm (CSA), that was created by Alireza Askarzadeh in 2016 [18]. It simulates the behavior of an intelligent bird (crow) in obtaining, hiding, and stealing food. The principles of CSA depend on some factors such as living in a swarm (flock or family), having a strong memory for their food storage locations, tracking each other to steal one another's food, and depending on their experience of thievery to avoid falling victim to the other birds [19]. Algorithmically, CSA is simple and easy structured. It has two design parameters only, and that makes it suitable for solving various engineering problems [20–23].

The optimal solution is compared with all the presented mathematical design methods, taking into account different technical performance indices such as harmonic distortion levels, filter efficiency, voltage amplification percentage, and the risk of filter failure. On the other hand, the economic side is considered through estimating the filtering cost of all the considered methods. A petrochemical plant, located in Egypt that suffers from continuous failure of electronic cards and programmable logic controller (PLC) devices has been taken as a case study in this research. Modeling and simulation results of the case study are carried out in the Matlab and ETAP environments.

The contribution of this work is twofold; firstly, a comprehensive overview of all reactive power-sharing approaches among multiple-arm passive filters is presented, and secondly a recent meta-heuristic optimization algorithm, CSA, for the design of multiple-arm passive filters is implemented, while taking into account various technical and economic power quality indices.

The article is organized into six sections as follows: Section 1 presents an introduction to the purpose of the study. Section 2 is dedicated to the design techniques and their mathematical formulation. Section 3 describes the case under study. Section 4 presents the proposed optimization technique. Section 5 presents the results and discussion. Section 6 is dedicated to the conclusions and future work.

2. An overview of multiple-arm passive filter design methods

In this section, eight design approaches will be used for the total reactive power division among the filter arms. The eight presented approaches cover all the existing approaches for reactive power division among multiple passive filter arms. Some of them were presented in the literature (research methods). The others were based on empirical studies, but are used in practice. All these methods will be presented in detail. It is assumed that reactive power of 70 kvar is to be divided between the 5th, 7th, and 11th filter arms to improve the power factor (PF) to an acceptable range (above 95%) and mitigate harmonic distortion. The filters will be detuned by 3% below the desired harmonic orders; that is, the 5th, 7th, and 11th orders will be tuned to the 4.85th, 6.79th, and 10.67th orders, respectively [24]. Also, the obtained capacitor sizes are approximated further to the nearest sizes available in the power quality markets.

2.1. Equal capacitance: Method 1

This method is widely used in practice as it is considered the simplest one. The filter bank reactive power is divided equally between the filter branches [13], so that:

$$Q = \frac{Q\text{Total}}{n} \tag{1}$$

where n is the number of filter branches. The reactive power of 70 kvar is to be divided equally between the 5th, 7th, and 11th filter arms, thus: $Q_5 = Q_7 = Q_{11} = 22.5$ kvar.

2.2. Fixed step division: Method 2

The filter reactive power is inversely proportional to its harmonic order, so to allow a quick division of the total reactive power among a group of filters, a fixed step for the reactive power among the branches of the filter will be empirically executed. For example, if Q is needed for the 5th harmonic order, then $Q/2$ will be needed for the 7th harmonic, $Q/4$ for the 11th, and so on [8]. Considering 70 kvar to be divided among the 5th, 7th, and 11th filter arms, thus

$$Q5 = 2Q7 \tag{2}$$

$$Q7 = 2Q11 \tag{3}$$

$$Q\text{total} = Q5 + Q7 + Q11 \tag{4}$$

Substituting Eqs. (2) and (3) into Eq. (4), thus: $Q_5 = 40$, $Q_7 = 20$, and $Q_{11} = 10$ kvar.

2.3. Harmonic Content: Method 3

This technique is based on the inverse relation between the reactive power required for *PF* improvement and the desired harmonic order to be filtered [14], as the required reactive power decreases when the harmonic order to be mitigated increases according to the relation below:

$$Q \propto \frac{1}{h} \tag{5}$$

where Q is the filter reactive power required for power factor correction and h is the desired harmonic order. Applying the above relation to the 5th, 7th, and 11th harmonic filters results in:

$$\frac{Q5}{Q7} = \frac{6.79}{4.85} \tag{6}$$

$$\frac{Q7}{Q11} = \frac{10.67}{6.79} \tag{7}$$

Substituting Eqs. (6) and (7) into Eq. (4), thus: $Q_5 = 32.5$, $Q_7 = 25$, and $Q_{11} = 15$ kvar.

2.4. Equal inductance: Method 4

The voltages across the capacitor terminals of two filters of orders (n, m) connected in parallel to mitigate their harmonic are given by [13]: