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A multi-objective approach to optimal placement and sizing of multiple active power filters using a music-inspired algorithm

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ABSTRACT

This paper proposes a new multi-objective framework for optimal placement and sizing of the active power filters (APFs) with satisfactory and acceptable standard levels. total harmonic distortion (THD) of voltage, harmonic transmission line loss (HTLL), motor load loss function (MLLF), and total APFs currents are the four objectives considered in the optimization, while harmonic distortions within standard level, and maximum allowable APF size, are modeled as constraints. The proposed model is one of non-convex optimization problem having a non-linear, mixed-integer nature. Since, a new modified harmony search algorithm (MHSA) is used and followed by a min–max technique in order to obtain the final optimal solution. The harmony search algorithm is a recently developed optimization algorithm, which imitates the music improvisation process. In this process, the Harmonists improvise their instrument pitches searching for the perfect state of harmony. The newly developed method has been applied on the IEEE 18-bus test system and IEEE 30-bus test system by different scenarios and cases to demonstrate the feasibility and effectiveness of the proposed method. The detailed results of the case studies are presented and thoroughly analyzed. The obtained results illustrate the sufficiency and profitableness of the newly developed method in the placement and sizing of the multiple active power filters, when compared with other methods.

1. Introduction

Nowadays, development of power electronic-based equipments connected to the electrical distribution networks leads to many difficulties such as harmonic current problems. Harmonic current by these non-linear loads can lead to waveform distortion of system voltages, torque pulsation, heating in rotating machines and transformers, higher losses, reducing the life age of devices, etc. [1,2]. Traditionally, one solution for harmonic problems has been passive R–L–C filters. Passive filters include resistance and tuned capacitance and inductance, which can be connected in series or parallel to the bus load. On the one hand, the passive R–L–C filters have large size and parallel resonance and on the other hand, these filters can be eliminated only a specific harmonic; therefore, active power filters (APFs) were developed in the 1970s to overcome passive filters problems [2]. Roughly speaking, the APFs inject equal-but-opposite currents to network as this current is a summation of total harmonic component in order to eliminate the non-sinusoidal components of the non-linear loads [3–6]. The first APF was used for harmonic compensation in 1982. The nominal power of this APF was 800 kVA. A hybrid filter by an APF with nominal power of 900 kVA and a passive filter with power rating of 6600 kVA was utilized in 1986 [7]. Also, more than one hundred APFs have been operating properly in JAPAN by Mitsubishi Company. Given the capabilities and abilities of the APFs, notably in the harmonic elimination, many studies have been concentrated on the APFs in recent decades [8–12]. A recent research issue involving the proper siting and sizing of APFs was named the optimal PLAcement and Sizing (PLAS) problem of the APFs [8–15]. In these studies, the size of APFs is determined by its maximum effective injection current. Also, harmonic standard constraints, APFs locations and sizes, existing harmonic pollution levels and network topology are main factors in the utilization of the APFs. There are many mathematical models available for solving the PLAS problem related to the APFs. The proposed models can be classified as two types of objective functions and two types of constraints [8–15]. The first types of objective functions minimize the voltage distortion to decrease the undesirable effects of harmonic distortions on the electrical distribution networks. The other types use harmonic standards on voltage harmonic distortion and total harmonic distortion (THD) levels to minimize the injected currents of APFs. The PLAS problem of the APFs basically represents an optimization problem in which different objective functions may be

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utilized: total harmonic distortion (THD), telephone influence factor (TIF), harmonic transmission line loss (HTLL), motor load loss function (MLLF), etc. [12–20]. The PLAS problem of a single APF is investigated in numerous studies [2–4,9,11–15], and multiple APFs in others [11,13]. In Refs. [5–10,15], the APFs size is reported as discrete variables; thus, the PLAS problem of APFs is modeled by a mixed-integer non-linear optimization problem (MINLP). The first types of constraints are harmonic standards applied to the level of voltage harmonics and THD in different locations according to the IEEE-519 standard [11–15]. The second type of constraint is maximum current of an APF (i.e., APF size), which it is due to APF itself. The APF size has a discrete nature because of discrete sizes of inductors and capacitors, which utilized in its structure. Thus, in the PLAS problem, the discrete variables are APFs size [5,10–15]. Consequently, the PLAS problem of APFs is a complicated optimization problem, which formulized as a mixed-integer non-linear problem. In the last decade, plenty of evolutionary optimization techniques have been used to solve the single-objective optimization problems such as genetic algorithms (GAs) [15,21], discrete particle swarm optimization (DPSO) [11,12,14], improved particle swarm optimization (IPSO) [22], Tabu search algorithm (TSA) [10], generalized benders decomposition theory (GBDT) [23] and Lyapunov function [24]. Moreover, lexicographic optimization along with augmented epsilon-constraint method [25,26], incorporating lexicographic optimization and hybrid augmented-weighted epsilon-constraint method [27], corrected normal boundary intersection (CNBI) method [28], fuzzy method and max–min operator [29,30] have also been utilized so as to solve the multi-objective optimization problems. These studies showed that there are some weaknesses both in modeling – such as incomprehensive of objective functions, single-objective optimization model, and in evolutionary optimization techniques – such as insufficient precision, convergence speed, ignorance of flexibility optimization techniques, etc.

This paper, then, concentrated on identifying a new multi-objective framework in order to solve PLAS problem of the APFs with satisfactory and acceptable standard levels. Optimization of the total APFs currents, namely, the APFs costs, THD of voltage, HTLL and MLLF are considered in this current study. Besides, the proposed PLAS problem takes into account four types of the APFs to enhance flexibility in control of harmonics. In order to obtain an optimum solution, a new modified harmony search algorithm (MHSA) is used and followed by a min–max technique, which is not trapped in a local minimum. Because of the compromised nature of the solutions and the role of human decision on the final solution of the multi-objective optimization problem, the min–max technique can be applied to solve the multi-objective problem. Also, in this study, by dynamically changing the pitch adjusting rate and the bandwidth parameters in any generation, search performance of the HSA will be modified. The newly developed method has been demonstrated on the IEEE 18-bus test system and IEEE 30 bus test system [11,13, 15 and 31] by three scenarios and cases to demonstrate the feasibility and usefulness of the proposed PLAS method. In order to the best of our knowledge, the main contributions of this paper over previous researches in the context of PLAS problem are threefold:

(1) A new multi-objective method based on THD, HTLL, MLLF, and total APFs currents to eliminate harmonic distortion in the electrical distribution network is taken into account.
(2) The flexibility of the proposed approach improves by using multiple active power filters (M-APFs) in the PLAS process. Due to existing harmonic pollution at high levels and low rating current of an APF; therefore, an APF cannot improve power quality as acceptable level.
(3) A new modified optimization algorithm is utilized to overcome the difficulties in solving the mixed-integer non-linear nature of the PLAS problem and determine the optimal final solution.

The rest of this paper is organized into six sections. Section 2 describes formulization of multiple active power filters in electrical distribution networks. The proposed placement and sizing problem of the multiple active power filters is presented in Section 3. In addition, solution algorithm of the proposed placement and sizing problem is presented in Section 4. Simulation results and case studies are demonstrated and discussed in Section 5. Finally, Section 6 is devoted to conclusions and further research.

2. Modeling of the M-APFs in the electrical distribution networks

In recent years, utilization and operation of reliable power devices have been increased in the electrical distribution networks for elimination of harmonics, phase balancing and power factor correction. One of the new reliable power devices used to improve quality of power delivered to the utilities is the APFs. Therefore, in this study, the PLAS problem of M-APFs has been considered to compensate harmonics and amend power quality in the electrical distribution networks and also prevent new installation of bulky passive filters [11–20].

2.1. APFs modeling in the electrical distribution network

The proposed model for the APFs in this study is a common model for the APFs and has been utilized in numerous studies [11–15]. This model is a current source, as it injects harmonic currents into the network. The Phasor model of each APF is addressed in Eq. (1).

$$(I_f)_b^h = [(I_f)_b^h]_r + j[(I_f)_b^h]_i; \quad \forall b = 1, 2, \ldots, B,\ \forall h = 1, 2, \ldots, H \tag{1}$$

The root mean square (RMS) current of each APF is also obtained according to Eq. (2).

$$(I_f)_b = \sqrt{\sum_{h=1}^{H} \left((I_f^2)_b^h\right)_r + \left((I_f^2)_b^h\right)_i}; \quad \forall b = 1, 2, \ldots, B \tag{2}$$

In addition, for a linear frequency domain analysis, the power system network is linearized; and for each frequency, all non-linear loads are regarded as current sources. Accordingly, the network impedance matrix can be obtained independently for each frequency [11,15].

3. Modeling of the PLAS problem of M-APFs in the electrical distribution networks

In this paper, a new multi-objective framework is addressed for the PLAS problem of the APFs. The proposed model simultaneously minimizes four objectives, namely the Total Cost of installed APFs, THD of voltage, HTLL and MLLF.

3.1. Total harmonic distortion (THD)

In this paper, the dependent function of total harmonic distortion is a standard formulation that used by many studies [11–20]. Therefore, the THD of voltage can be obtained as follows:

$$\mathrm{THD} = \sum_{b=1}^{B} \mathrm{THD}_b; \quad \forall b = 1, 2, \ldots, B \tag{3}$$