Applied Soft Computing 35 (2015) 257–266

Contents lists available at ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

Optimal design of passive power filters based on multi-objective bat algorithm and pareto front

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ARTICLE INFO

Article history:
Received 31 August 2014
Received in revised form 2 February 2015
Accepted 30 May 2015
Available online 2 July 2015

Keywords:
Bat algorithm
External archive
Multi-objective optimization
Non-dominated solutions
Passive power filters

ABSTRACT

This paper proposes an optimal design method for passive power filters (PPFs) in order to suppress critical harmonics and improve power factor. The characteristics of common passive filters, such as single-tuned, second-order, third-order, and C-type damped filters are introduced. In addition, several objective functions and constraints for PPF design problems are constructed. A new multi-objective optimization based on the modified bat algorithm and Pareto front is developed for solving PPF design problems. A case study is also presented to demonstrate the efficiency and superiority of the proposed method.

1. Introduction

Nowadays, in modern power systems, nonlinear loads that may produce many harmonics are increasingly used, especially in electronic devices [1]. Harmonics distort current and voltage waveforms, which are expected to be purely sinusoidal. If the distortion is sufficiently large, it may lead to unfavorable effects, such as communication interference, power loss, equipment heating, malfunction, or even damage. In order to reduce harmonic effects, power filters are widely used in electric power systems. In addition to harmonic mitigation, power filters can provide reactive power compensation, which can improve the system power factor and reduce power loss. In general, there are three types of power filters: passive power filters (PPFs) [2–5], active power filters [6,7], and hybrid power filters [8]. Among them, PPFs have been used more commonly than the other types because of their low cost and simplicity.

Designing PPFs includes determining the types, set number, elements, and parameters of filters to satisfy the requirements of harmonic filtering, power factor compensation, and other conditions [4,8]. That is, the performance of PPFs is determined not only by circuit topology but also by the values of the resistive, inductive, and capacitive components [5]. Designing a PPF is a difficult task owing to the several nonlinear constraints and objectives that have to be considered. Based on the experiences of engineers, trial-and-error procedures are involved in conventional methods. However, optimal solutions of PPFs are difficult to obtain. Recently, the growth of nature-inspired optimization methods has opened new approaches for PPF designs. Genetic algorithm-based methods have been used in PPF design [5], but their main disadvantages include a high computational burden and low convergence rate. Particle swarm optimization (PSO)-based methods are inspired by the social behaviors of a bird flock or a fish school when searching for food. The PSO algorithm [9] is known to have fast convergence and has been proved to be very successful with single-objective optimization problems. Some PSO-based methods have also been applied to PPF design [3,8]. Most of them treat the optimal design of PPFs as a single-objective optimization problem using a combinatorial fitness function [3], or they attempt to transform a multi-objective problem into a single-objective one by considering two or more objective functions as "acceptable level" constraints [8]. In a multi-objective optimization task, there is a set of feasible solutions called the *Pareto optimal set*. The values of the objective functions are used together to form a so-called *Pareto front*. In addition, these solutions can be termed as non-dominated solutions. Generally, in order to extend the PSO algorithm for multi-objective optimization, an external archive is usually used to store non-dominated solutions. In addition, the search space of variables is divided into many hyper-cubes which can help obtain a well-distributed Pareto front.

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http://dx.doi.org/10.1016/j.asoc.2015.05.042
1568-4946/

New nature-inspired optimization methods are still being developed. A noteworthy example of those, called the bat algorithm (BA), was proposed by Yang [10] and has a promising future. This method is inspired by the echolocation behavior of microbats and has been proved to be efficient in some practical applications [11,12]. This paper proposes a new multi-objective optimization method based on the modified BA and Pareto front for PPF design. With the proposed approach, the PPFs design can be treated as a real multi-objective problem. No combinatorial functions or "acceptable level" constraints need to be used. In addition, several solutions are obtained, which can offer several options to a designer for selecting a suitable result.

2. Passive power filters

Compared to other methods and other types of filters, PPFs are widely used for mitigating harmonic effects in power systems because of their low cost and simplicity. The filters are usually installed close to the nonlinear loads, which may produce harmonic currents. After being installed, the filters can provide a low-impedance path to critical harmonic currents, and hence, prevent harmonic currents from flowing into the systems. In general, a PPF is composed of passive elements such as resistors, inductors, and capacitors. Fig. 1. shows typical PPFs including a single-tuned filter, second-order damped filter, third-order damped filter, and C-type damped filter.

2.1. Single-tuned filters

The single-tuned filter is a series combination of an inductor, a capacitor, and a resistor. The resistor is usually considered to be the intrinsic resistance of the inductor or the capacitor. Single-tuned filters have a very simple configuration. Hence, it offers low investment cost and power loss. However, the filter can attenuate only a single harmonic-order component. The transfer function of the single-tuned filter can be expressed as follows:

$$Z_F(s) = \frac{1}{s}\left[\left(\frac{s}{\omega_n}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_n}\right) + 1\right] \quad (1)$$

where s is the complex frequency, Q is the quality factor, and ω_n (or f_n) is the resonant frequency in rad/s (or Hz).

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \quad (2)$$

$$\omega_n = \frac{1}{\sqrt{LC}} \rightarrow f_n = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

The impedance magnitude at the resonant frequency is represented by a valley in the plot of the magnitude response shown in Fig. 2. If the quality factor is increased, the resonant valley will become sharper, resulting in better harmonic attenuation. The resonant harmonic order is given by

$$h_n \triangleq \frac{f_n}{f_1} = \frac{1}{2\pi f_1\sqrt{LC}} = \frac{1}{\omega_1\sqrt{LC}} \quad (4)$$

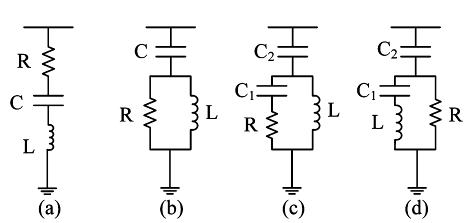

Fig. 1. Typical PPFs: (a) single-tuned filter, (b) second-order damped filter, (c) third-order damped filter, and (d) C-type damped filter.

According to (4), the relationship between the fundamental inductive reactance X_L and the fundamental capacitive reactance X_C can be expressed as follows:

$$X_L = \frac{X_C}{h_n^2} \quad (5)$$

At the h^{th}-order harmonic frequency, the impedance of single-tuned filters is calculated as follows:

$$\bar{Z}_{Fh} = R + j\left(hX_L - \frac{X_C}{h}\right) \quad (6)$$

2.2. Second-order damped filters

The second-order damped filter is a high-pass filter. It can attenuate harmonic currents whose frequencies are above the resonant frequency. In the s-domain, the transfer function of the filter is given by

$$Z_F(s) = \frac{R}{Cs(sL+R)}\left[\left(\frac{s}{\omega_n}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_n}\right) + 1\right] \quad (7)$$

The quality factor is obtained as follows:

$$Q = \frac{R}{\sqrt{L/C}} \quad (8)$$

The magnitude response of the filter is shown in Fig. 3. The resonant frequency, resonant harmonic order, and the relationship between X_L and X_C are calculated by (3), (4), and (5), respectively. At the h^{th}-order harmonic frequency, the filter impedance is calculated as follows:

$$\bar{Z}_{Fh} = \frac{R(hX_L)^2}{R^2 + (hX_L)^2} + j\left[\frac{R^2 hX_L}{R^2 + (hX_L)^2} - \frac{X_C}{h}\right] \quad (9)$$

2.3. Third-order and C-type damped filters

In the third-order damped filter, a capacitor is connected in series with the resistor for reducing the impedance of the resistor branch. As a result, the fundamental power loss will decrease. Generally, the two capacitors of the third-order damped filter are selected similarly for design simplicity. Meanwhile, in the C-type damped filter, a capacitor is connected in series with the inductor instead of the resistor to yield series resonance at the fundamental frequency. This connection scheme is also aimed to reduce the fundamental power loss caused by the resistor. For these two filters, two parameters are introduced as the characteristic harmonic order h_n and damping constant ratio m given as follows:

$$h_n = \frac{1}{2\pi f_1 R C_2} \quad (10)$$

$$m = \frac{L}{R^2 C_2} \quad (11)$$

The magnitude response of the third-order and C-type damped filters are represented in Fig. 4 and Fig. 5, respectively. At the h^{th}-order harmonic frequency, the impedance of the third-order damped filter is given by

$$\bar{Z}_{Fh} = \frac{R(hX_L)^2}{R^2 + \left(hX_L - \frac{X_C}{h}\right)^2} + j\left[\frac{R^2 hX_L - hX_L^2 X_C + \frac{X_L X_C^2}{h}}{R^2 + \left(hX_L - \frac{X_C}{h}\right)^2} - \frac{X_C}{h}\right] \quad (12)$$

and the impedance of the C-type damped filter is given by:

$$\bar{Z}_{Fh} = \frac{R\left(hX_L - \frac{X_L}{h}\right)^2}{R^2 + \left(hX_L - \frac{X_L}{h}\right)^2} + j\left[\frac{R^2\left(hX_L - \frac{X_L}{h}\right)}{R^2 + \left(hX_L - \frac{X_L}{h}\right)^2} - \frac{X_C}{h}\right] \quad (13)$$