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Genetic algorithm-based optimal design of shunt compensators in the presence of harmonics

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Abstract

This paper presents a genetic algorithm (GA)-based approach for the optimal design of passive shunt compensators when a nonideal, nonsinusoidal voltage source supplies a linear load. In contrast to traditional optimization techniques, the proposed GA has the following combined advantages: it allows both topological structure and component sizes of a compensator of any complexity to be optimized by introducing variable-length chromosomes. It is easy to change constraints or apply new ones using a death penalty or an adaptive penalty scheme for handling constraints. No preliminary calculations are necessary to identify resonant conditions in advance. Simulation results on an example system show the way and the extent to which the various apparent power components and other significant quantities are affected by compensation. An almost unity power factor is possible using a Foster form compensating circuit.

Keywords: Power system harmonics; Power factor; Compensation; Optimization; Genetic algorithms

1. Introduction

Power factor correction under sinusoidal conditions has been well established. The application of a power capacitor is sufficient to achieve a unity power factor at the load. Power factor correction under nonsinusoidal conditions with an ideal voltage source (zero source impedance) by means of a capacitor has also been established [1–4]. In this case, an analytical solution has been derived for the optimum capacitor value. Since the voltage, as well as the active power, are identical before and after compensation, maximum power factor also means minimum apparent power or minimum source current. In general, a capacitor can compensate only partly specific components of the apparent power; consequently, the maximum possible value of the power factor using only a capacitor is less than unity. A further improvement in the power factor is also possible, as shown in [5,6]. This can be achieved by using more complex one-port reactive compensating circuits. An almost unity power factor may then be attained.

Power factor correction under nonsinusoidal conditions with a nonideal voltage source (nonzero source impedance) using a capacitive compensator (C) was treated in Ref. [7]. Two major points were revealed in this work concerning this case. First, an analytical solution for the optimal capacitor value is not possible. Hence, one has to formulate and solve this problem as a nonlinear optimization problem. To this end, the traditional Golden Section search algorithm was used. Second, the compensating capacitor and the source impedance set up a resonant circuit. If the resonance frequency is at, or close to, a harmonic frequency of the source, excessive harmonic currents and/or voltages may arise. Such currents and voltages can have detrimental effects on the equipment. This fact imposes possible constraints on the capacitor values. It is also worthwhile to note that, in this case, neither the load voltage nor the active power are identical before and after compensation. Consequently, maximum power factor is not exactly equivalent to minimum apparent power or minimum source current. In order to avoid resonant conditions and further improve performance, a detuning reactor L in series with the capacitor C (LC compensator) has been studied

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[8–14]. However, to achieve the highest possible power factor and simultaneously meet minimum operational and power quality requirements a sufficiently complex compensating circuit has to be designed [15,16].

In this paper, a genetic algorithm is presented as the searching technique for the optimal design of reactive shunt compensators under nonsinusoidal conditions with a nonideal voltage source. Three different compensating circuit configurations are examined. Even for a pure capacitive or an *LC* compensator, the GA offers advantages with respect to the traditional optimization techniques usually employed. This is especially true if tight inequality constraints are imposed on the acceptable solutions. More importantly, the proposed GA can be used as the optimization tool for the design of a more complex compensating circuit. By using a Foster form circuit the maximum possible compensation can be obtained. The importance lies in the fact that besides a multivariable numerical optimization, the optimization of the topological structure (number and type of branches) is also possible. This can be handled by introducing a variable-length chromosome concept.

2. Circuit model of the system under study

2.1. Voltages, currents and powers

The equivalent circuit of the system under study is shown in Fig. 1. A linear load is supplied by a nonideal, nonsinusoidal voltage source. A one-port reactive shunt compensator is used to improve the power factor.

Symbols refer to the rms values of voltages and currents as well as the source, load and compensator impedances, all for the harmonic of order *h*. For the complex values of these quantities, one can easily derive the following relations based on simple current and voltage divider concepts:

$$\underline{I}_h = \frac{\underline{V}_{Sh}(\underline{Z}_{Ch}+\underline{Z}_{Lh})}{\underline{Z}_{Sh}\underline{Z}_{Ch}+\underline{Z}_{Sh}\underline{Z}_{Lh}+\underline{Z}_{Ch}\underline{Z}_{Lh}} = \frac{\underline{V}_{Sh}(\underline{Y}_{Sh}\underline{Y}_{Lh}+\underline{Y}_{Sh}\underline{Y}_{Ch})}{\underline{Y}_{Lh}+\underline{Y}_{Ch}+\underline{Y}_{Sh}} \tag{1}$$

$$\underline{V}_h = \frac{\underline{V}_{Sh}\underline{Z}_{Ch}\underline{Z}_{Lh}}{\underline{Z}_{Sh}\underline{Z}_{Ch}+\underline{Z}_{Sh}\underline{Z}_{Lh}+\underline{Z}_{Ch}\underline{Z}_{Lh}} = \frac{\underline{V}_{Sh}\underline{Y}_{Sh}}{\underline{Y}_{Lh}+\underline{Y}_{Ch}+\underline{Y}_{Sh}} \tag{2}$$

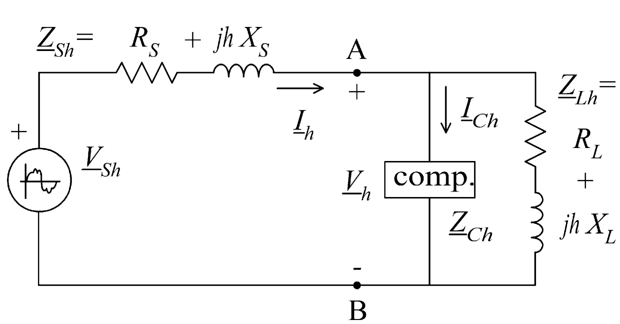

Fig. 1. The circuit model.

$$\underline{I}_{Ch} = \frac{\underline{V}_{Sh}\underline{Z}_{Lh}}{\underline{Z}_{Sh}\underline{Z}_{Ch}+\underline{Z}_{Sh}\underline{Z}_{Lh}+\underline{Z}_{Ch}\underline{Z}_{Lh}} = \frac{\underline{V}_{Sh}\underline{Y}_{Ch}\underline{Y}_{Sh}}{\underline{Y}_{Lh}+\underline{Y}_{Ch}+\underline{Y}_{Sh}} \tag{3}$$

where

$$\underline{Y}_{\cdot h} = \frac{1}{\underline{Z}_{\cdot h}} = \frac{1}{R_{\cdot}+jX_{\cdot h}} = \frac{R_{\cdot}}{R_{\cdot}^2+X_{\cdot h}^2} - j\frac{X_{\cdot h}}{R_{\cdot}^2+X_{\cdot h}^2} = G_{\cdot h} - jB_{\cdot h} \tag{4}$$

The dot stands for any one of the indexes *S*, *C*, or *L*. Moreover, $\underline{Y}_{\cdot h}$, $G_{\cdot h}$, $B_{\cdot h}$ are the corresponding admittance, conductance and susceptance, respectively, for the harmonic of order *h*. Using the generic symbol A_h for any harmonic voltage or current, the corresponding rms value for the combined harmonics is:

$$A = \left(\sum_h A_h^2\right)^{1/2} \tag{5}$$

Concerning active power *P* and apparent power *S* at the terminals AB one can write:

$$P = \sum_h P_h = \sum_h V_h I_h \cos\varphi_h \tag{6}$$

$$S = VI \tag{7}$$

where φ_h is the phase angle between $\underline{V}_h$ and $\underline{I}_h$. Moreover, the displacement power factor (DPF) and the total power factor (PF) are defined as:

$$\mathrm{DPF} = \frac{P_1}{V_1 I_1} = \cos\varphi_1 \tag{8}$$

$$\mathrm{PF} = \frac{P}{S} \tag{9}$$

According to Ref. [3], the apparent power *S* can be decomposed into two components S_R, S_X as follows:

$$S^2 = S_R^2 + S_X^2 = \left(\sum_h V_h^2 \sum_h I_h^2 \cos^2\varphi_h\right) + \left(\sum_h V_h^2 \sum_h I_h^2 \sin^2\varphi_h\right) \tag{10}$$

Under the assumption of an ideal source, a shunt reactive compensator can compensate partly or wholly the component S_X. The component S_R remains unchanged. It will be shown later that this is not the case when the source is nonideal. In order to have a better perspective on the effects of a compensator on the apparent power components, a further decomposition [17] is adopted here, i.e.:

$$S^2 = S'^2_R + S''^2_R + S'^2_X + S''^2_X = \sum_h (V_h I_h \cos\varphi_h)^2 + \sum_{h'\neq h} (V_{h'} I_h \cos\varphi_h)^2 + \sum_h (V_h I_h \sin\varphi_h)^2 + \sum_{h'\neq h} (V_{h'} I_h \sin\varphi_h)^2 \tag{11}$$

Without any further explanations, one can say that like-frequency components S'_R, S'_X are associated with active and