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Optimal installation of three-phase active power line conditioners in unbalanced distribution systems

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Abstract

In this paper, a new solution algorithm based on a multiple gradient summation (MGS) and differential evolution (DE) approach for optimal three-phase active power line conditioners (APLCs) installation in unbalanced distribution systems is proposed. The active power line conditioners installation problem considers the individual and total harmonic voltage distortions as well as the commercially available discrete sizes of the APLCs limits to minimize the total sizes of three-phase APLCs. The imbalance of systems resulting from using asymmetrical connection transformers was taken into account. The effectiveness of the proposed method was demonstrated by its application to a 23-bus unbalanced radial distribution system.

Keywords: Active power line conditioner; Total harmonic voltage distortion; Differential evolution; Multiple gradient summation method

1. Introduction

The use of nonlinear loads in power systems can create harmonic currents. These harmonic currents can cause voltage and current distortion throughout the system, which can result in additional losses, measurement errors and malfunctions of protection devices [1–4]. In addition, the use of asymmetrical connection transformers in systems may cause worse harmonic pollution. Passive shunt filters and active power line conditioners (APLCs) can be employed to reduce the harmonic distortion. The cost of a passive filter is lower than that of an APLC, but it may cause resonance in the power system. On the contrary, the APLC does not resonate with the supply impedance. Consequently, the active power line conditioner is deemed the most efficient device for reduction of the harmonic level [5].

In the last few years, several articles have been devoted to the study of using APLCs to reduce harmonic distortions in power systems. In [6–8] an APLC has been considered to minimize network harmonic voltage. Nevertheless, employing an APLC may not guarantee meeting the harmonic limits at each bus, when the power system involves many nonlinear loads. Multiple APLCs were considered to control harmonic voltage distortions [9–11]. Although this approach can solve the harmonic distortion problem for balanced systems, it may underestimate the harmonic distortion levels for unbalanced systems. Three-phase APLCs are utilized to mitigate harmonic pollution for an unbalanced system [12], however, the method employed may cause the solution to be trapped in a local optimum and the power flow program may diverge when rigorous transformer models are adopted.

The primary objective of active power line conditioner planning is to determine the locations and sizes as well as the injection current spectra of APLCs to meet the harmonic standard such that the total sizes of APLCs can be minimized. The injection current spectra of APLCs are continuous variables, but the sizes of the commercially available APLCs are discrete values. Hence, the APLCs installation problem is difficult to solve by an analytic method [6–12].

This paper develops a new solution algorithm for solving the three-phase APLC installation problem. Owing to the difficulty of the APLCs installation prob-

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lem, we solve it in two stages in the proposed approach. First, the constraint on discrete sizes of APLCs was released, and the multiple gradient summation method (MGS) [14] was employed to solve the resulting continuous nonlinear programming sub-problem. Secondly, the differential evolution method (DE) was employed to account for discrete sizes of APLCs, and to further improve the solution quality. Due to the capability to deal with the continuous nonlinear programming problem, the MGS is employed to find high quality approximate solutions, which will be used as parts of the initial vector population for the DE. DE is a new stochastic and parallel search method with ability to handle non-differential and nonlinear functions. It converges faster and with more certainty than many other global optimization methods [15]. In view of this, the DE method was adopted to quickly find the optimal solution. Making use of the advantages of both MGS and the DE method, the proposed approach was shown to be effective for the APLC installation problem. To consider the imbalance caused by using asymmetrical connection transformers, and improve the power flow program convergence, integrated models of distribution transformers and their loads were used [13].

2. Description of problem

The APLC installation problem considered in this paper is to determine the locations, sizes and injection current spectra of three-phase APLCs. The objective is to minimize the total sizes of the APLCs while satisfying the harmonic voltage distortion limits. Furthermore, the commercially available discrete sizes of APLCs and the imbalance caused by the use of asymmetrical connection transformers should be accounted for. The APLC installation problem can be expressed as follows:

$$\text{Min } F = \sum_{p=a,b,c} \sum_{k\in S_f} \sum_{h\in S_h} (I_{k,p}^{h,r})^2 + (I_{k,p}^{h,i})^2 \tag{1}$$

subject to:

$$|V_{i,p}^h|/|V_{i,p}^l| \le V_{\max}^h \quad i=1, \ldots, n_b; \quad h\in S_h,\ p=a, b, c \tag{2}$$

$$\sqrt{\sum_{h\in S_h} |V_{i,p}^h|^2} \Big/ |V_{i,p}^l| \le \text{VTHD}_{\max} \quad i=1, \ldots, n_b; \quad p=a, b, c \tag{3}$$

$$I_{k,p} = \left[\sum_{h\in S_h} (I_{k,p}^{h,r})^2 + (I_{k,p}^{h,i})^2\right]^{1/2} \in S_{size} \quad k\in S_f; \quad p=a, b, c. \tag{4}$$

Constraint Eq. (2) ensures that the individual harmonic voltage distortion for each bus is within the limit, and $V_{\max}^h$ is usually 3%. Constraint Eq. (3) ensures that the total harmonic voltage distortion for each bus is within the limit, and $\text{VTHD}_{\max}$ is usually 5%. Eq. (4) denotes that the sizes of APLCs are discrete in nature.

S_h the set of harmonic orders, it has n_h elements
S_f the set of bus installations of the APLCs, it has n_f elements
S_{size} $\{I_b, 2I_b, \ldots, mI_b\}$
I_b the base unit size of the APLC
mI_b the maximum size of the APLC
n_b the total number of the system bus
$I_{k,p}^{h,r}$ the real part of the APLC current of phase p at bus k for harmonic h
$I_{k,p}^{h,i}$ the imaginary part of the APLC current of phase p at bus k for harmonic h
$I_{k,p}$ the rms current of the APLC of phase p at bus k
$V_{i,p}^h$ the harmonic voltage of phase p at bus i for harmonic h
$V_{i,p}^l$ the fundamental frequency voltage of phase p at bus i

The harmonic voltage of phase p at bus i for harmonic h can be written as:

$$V_{i,p}^h = \sum_{k\in S_r} z_{ik,p}^h I_{k,p}^h + V_{io,p}^h, \tag{5}$$

where,

$z_{ik,p}^h = R_{ik,p}^h + jX_{ik,p}^h$
$I_{k,p}^h = I_{k,p}^{h,r} + jI_{k,p}^{h,i}$
$V_{io,p}^h = V_{io,p}^{h,r} + jV_{io,p}^{h,i}$
$z_{ik,p}^h$ the ikth element of the bus impedance of phase p for harmonic h
$R_{ik,p}^h$ the real part of $z_{ik,p}^h$
$X_{ik,p}^h$ the imaginary part of $z_{ik,p}^h$
$V_{io,p}^h$ the harmonic voltage of phase p at bus i for the original system
$V_{io,p}^{h,r}$ the real part of $V_{io,p}^h$
$V_{io,p}^{h,i}$ the imaginary part of $V_{io,p}^h$

Substituting Eq. (5) into Eqs. (2) and (3), respectively, we obtain:

$$G_{i,p}^h = \left|\sum_{k\in S_f} z_{ik,p}^h I_{k,p}^h + V_{io,p}^h\right| \le |0.03 V_{i,p}^l| \quad i=1, \ldots, n_b; \quad h\in S_h,\ p=a, b, c \tag{6}$$

$$H_{i,p}^t = \left\{\sum_{h\in S_h} \left|\sum_{k\in S_f} z_{ik,p}^h I_{k,p}^h + V_{io,p}^h\right|^2\right\}^{1/2} \le |0.05 V_{i,p}^l| \quad i=1, \ldots, n_b,\ p=a, b, c. \tag{7}$$