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Optimal passive filter planning considering probabilistic parameters using cumulant and adaptive dynamic clone selection algorithm

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ABSTRACT

Power quality in distribution systems may deteriorate due to increased time-varying and nonlinear loads. The harmonic current is one of the probabilistic and nonlinear pollution sources causing voltage distortion. The harmonic currents and bus loads in a power system are non-deterministic in nature. The single-tuned passive filter is considered an economical but efficient approach in reducing harmonics. This paper presents a new method for studying passive filter planning using cumulants and the Adaptive Dynamic Clone Selection Algorithm (ADCSA). The harmonic voltages, calculated by cumulants, correspond to those whose values of cumulative probabilities are 0.95. ADCSA was employed because of its ability to search the global optimum. The number (integer) of capacitor bank and tuned resonance frequency (real number) of the single-tuned passive filter are considered unknowns. The simulation results from an 18-bus system with multiple time-varying loads and harmonic currents show the applicability of the proposed method.

1. Introduction

The applications of nonlinear loads continue to increase thanks to improved power electronic technology. In addition, nonlinear loads resulting from saturated transformers or arc furnaces exist in the power system. The harmonic problems, e.g., voltage distortion and resonance, caused by the power electronic equipment and nonlinear loads have become increasing serious. Voltage distortions may lead to facility malfunctions and parallel/series resonances may result in facility overvoltage or overcurrent. Therefore, it is essential to design a filter for reducing the system harmonics to acceptable limits to maintain power quality, while keeping investment costs as low as possible.

Passive filters provide an economical alternative to reduce harmonics in the power system. The capacitor size and tuned resonance frequency need to be determined for the single-tuned filter, which is the most popular passive filter. When designing a single-tuned filter, some important factors must be considered: (a) multi-feeder and multi-bus structure, (b) time varying harmonic sources, (c) discrete capacitor sizes, (d) locations, (e) cost, (f) harmonic standard, (g) tuned resonance frequency, and (h) time varying linear load. Past studies [1–7] have addressed only parts of the above factors (a) through (h) and the number of buses in some studied systems is small.

Specifically, the bus linear load and nonlinear harmonic injection are time-varying and non-stationary in the system. The worst case (the largest harmonic currents and smallest linear loads) was considered for studying the passive filter planning in most existing papers. Higher investment cost will be attained and parts of the filters should be switched off due to over-compensation. Therefore, Chang et al. proposed a method considering these time-varying factors related to harmonics and load with Gaussian distribution in [1]. However, the harmonics may be other probability distributions or irregular patterns (e.g., arc furnaces). Confidence-level treatment in [1] cannot be used for other distribution patterns. Hong and Huang proposed fuzzy models for harmonics, loads and short-circuit capacity in [2]. This method tends to produce an optimistic solution because the triangle membership functions and minimal cost were considered [2]. Chang and Wu considered nonlinear arc furnace loads with different probabilities for gaining the expected investment in [3]. Actually, probabilistic model and convolution calculation were not utilized for attaining the optimal solution in [3].

Genetic algorithm [1,2,7], differential evolution algorithm [3], and partial swarm optimization [5] for designing the passive filter were used by the existing methods. These methods can effectively deal with the constraints, and continuous and integer variables. However, these algorithms, with concepts of stochastic search and large population size, will require an extremely long CPU time to gain an optimal solution. The inherent structure theory network [5], on the other hand, only determines strategic buses for harmonic filter placement and does not guarantee an optimal

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investment cost. In [6], sequential neural-networks were trained to simulate a rough map of the feasible domain formed by the constraints using a few representative training data. Large CPU times were taken to search the "optimal" investment and no tuned frequencies were considered. The factors of time-varying harmonics and linear loads are extremely important and were ignored in [4–7].

When the probabilistic or stochastic distributions are modeled for studied signals, convolution should be conducted for signal multiplication and addition operations. However, convolution requires massive CPU times. Cumulants serve a feature extraction from a signal distribution and can avoid complicated convolution computation. Recently, cumulants were used to solve the probabilistic power flow in the transmission system in [8]. Cumulants were also applied to solve optimal reactive power flow in a distribution system considering wind farms in [9]. These studies show cumulants have the potential to efficiently solve non-stationary, irregular and time-varying signals.

On the other hand, immune algorithms are population-based programming methods for searching the global optimum in a nonlinear non-convex space. Immune algorithms can be considered an enhanced genetic algorithm including crossover, mutation and selection operations. Immune algorithms have some diverse algorithmic steps [10]. An immune quantum evolutionary algorithm based on the chaotic searching technique was proposed for global optimization [11]. The immune algorithm was used to derive the optimal placement of switching devices by minimizing the total cost of customer service outage and investment cost of line switches in [12]. The immune algorithm was also used to determine the capacitor placement in [13]. The practical capacitor operating constraints, load profiles, feeder capacities and allowable voltage limits at different load levels are considered while the investment cost and energy loss are minimized [13]. Incorporated with niche technology, the immune genetic algorithm in dealing with multi-peak model function optimization was enhanced to solve a bid-based dynamic economic dispatch problem in [14]. An artificial immune system based on the clonal selection principle for solving dynamic economic dispatch problem was proposed in [15]. This approach implemented adaptive cloning, hyper-mutation, aging operator and tournament selection [15]. Clonal selection based artificial immune system algorithm was used to solve the dynamic economic dispatch problem for generating units with valve-point effect in [16]. The Taguchi method incorporated with the traditional immune algorithm in the crossover operations for selecting the better gene was presented to deal with the unit commitment problem in [17]. These studies show that the immune-based algorithms have potential for applications of the power system analysis.

In this paper, a new immune-based method incorporating cumulants is proposed to investigate optimal passive filter planning. The above factors (a)–(h) are considered; especially, the time-varying and irregular harmonics and linear loads are modeled by the cumulants. The discrete capacitor size and continuous tuned frequency for each single tuned filter are determined. The harmonic voltage corresponding to the one whose cumulative probability is 95% is considered the representative voltage, which should be subject to IEEE Std 519. The immune-based Adaptive Dynamic Clone Selection Algorithm (ADCSA) [18] is used to optimize the locations and sizes of filters in a distribution system with multiple buses and multiple feeders.

This paper is organized as follows: The problem formulation is provided in Section 2. Section 3 presents the probabilistic harmonic power flow using cumulants. The ADCSA-based method for solving the optimal filter planning is proposed in Section 4. The simulation results from an 18-bus distribution system are discussed in Section 5. Concluding remarks are given in Section 6.

2. Problem formulation

Let the symbols P, H, Nb be the sets of filter candidate buses, total harmonics orders and total bus number, respectively. As described in Section 1, the optimal filter planning problem can be formulated as follows:

$$\text{Min } f = \sum_{i\in P}\sum_{h\in H} TC_{hi} \tag{1}$$

subject to

$$[\tilde{Y}_h] \times [\tilde{V}_h] = [\tilde{I}_h],\ \ h \in H \tag{2}$$

$$(h-1) \leqslant m_{hi} \leqslant 0.92 \times h,\ \ h \in H,\ \ i \in P \tag{3}$$

$$Q_{hi} \leqslant Q_{hi}^{\max},\ \ h \in H,\ \ i \in P \tag{4}$$

$$V_{hj} \leqslant V_{hj}^{\max},\ \ h \in H,\ j \in Nb \tag{5}$$

$$\sqrt{\sum\nolimits_{h\in H} (V_{hj})^2} \leqslant THD_V^{\max},\ \ h \in H,\ j \in Nb \tag{6}$$

Total cost TC_{hi} for a filter in Eq. (1) can be expressed as follows [2]:

$$TC_{hi} = K_C\left[Q_{hi} + \left(\frac{\tilde{I}_{hi}^2 V_i^2}{Q_{hi} m_{hi}}\right)\right] + K_L\left[\frac{Q_{hi}}{m_{hi}^2} + \left(\frac{\tilde{I}_{hi}^2 V_i^2}{Q_{hi} m_{hi}}\right)\right] \tag{7}$$

where $\tilde{I}_{hi}$ is the probabilistic hth harmonic current through the filter at candidate bus i. The symbol V_i is the magnitude of the fundamental voltage at candidate bus i. K_C and K_L (3.5 p.u./kVAr and 8 p.u./kVAr) are the unit cost for the capacitor and inductor, respectively. The symbol Q_{hi} and m_{hi} are the net fundamental frequency reactive power and tuned resonance frequency for harmonic h at bus i, respectively. The superscript "max" denotes the maximum limits. In this problem, the hth harmonic voltage V_{hj} at bus j is the state variable while Q_{hi} and m_{hi} are the control variables. There are several comments for the above equations:

(a) The characteristics of time-varying linear loads and harmonic currents are modeled by probabilistic (or stochastic) distributions in this paper. Eq. (2) depicts the probabilistic (stochastic) harmonic penetration study. $[\tilde{Y}_h]$, $[\tilde{V}_h]$, and $[\tilde{I}_h]$ denote the probabilistic (stochastic) harmonic Y-matrix, vector of probabilistic (stochastic) harmonic voltages and vector of probabilistic (stochastic) harmonic currents, respectively. The voltage-independent harmonic injection current model, e.g., Eq. (2), is widely used [1,2,5,7]. Other works considered a more complicated model, e.g., voltage-dependent harmonic current. When the voltage-dependent harmonic current model is considered, the solution process for obtaining harmonic voltages requires iterations. However, if harmonic voltages are within constraints due to filter installation, then the voltages are close to the nominal values and the harmonic currents are nearly voltage-independent.

(b) The diagonal terms of $[\tilde{Y}_h]$ may include two terms: one is the filter harmonic admittance for a passive filter as follows [2]:

$$Y_{hi} = \frac{Q_{hi} h (m_{hi}^2 - 1)}{h^2 - m_{hi}^2} \tag{8}$$

The other term is the admittance of the probabilistic (stochastic) linear load. These linear loads will expressed in terms of cumulants.

(c) There are some treatments for the hth harmonic voltage V_{hj} at bus j. In [1], the probability constraint of the harmonic voltage expressed by the chance-constrained programming model was employed to limit the bus voltage within the required probability level. In this paper, a similar concept of IEC Std 61000-3-6 is considered [19]. That is, the V_{hj} will be the one whose value of the cumulative probability is 0.95.