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# Capacitor and passive filter placement in distribution systems by nondominated sorting genetic algorithm-II

Jandecy Cabral Leite[a], Ignacio Pérez Abril[b,*], Manoel Socorro Santos Azevedo[c]

[a] Institute of Technology and Education Galileo of Amazonia (ITEGAM), Praça Francisco Pereira da Silva, 149 Manaus, Brazil
[b] Universidad Central "Marta Abreu" de Las Villas, Centro de Estudios Electroenergéticos, Carretera de Camajuaní km 5, Santa Clara, Villa Clara, Cuba
[c] Universidad do Estado de Amazonas (UEA), Escola Superior de Tecnologia, Ave. Darcy Vargas, 1200—Parque 10, Manaus, Brazil

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ABSTRACT

The optimization of passive filters in distribution systems has been addressed through different approaches. In general, these approaches can be classified as single-objective and multi-objective formulations. The single-objective formulations normally try to determine the least costly filters that ensure compliance with the relevant power quality standards. In multi-objective approaches, other goals are added. In general, most studies consider the reactive power of filters at a fundamental frequency to be equal to a previously determined magnitude, and the optimization is devoted to calculate the other parameters of the filters that are required to minimize the distortion indices of the network. In the present approach, the capacitor placement and passive filter placement problems are considered as a unified problem in which a set of passive compensators (capacitors and/or tuned filters) that allow to obtain the maximum annual saving in cost and maximum improvement of the power quality of the circuit are determined. In this study, the annual saving is calculated as the equivalent present value of the compensation project to simultaneously account for the benefits of the reactive power compensation and the cost of investment in the compensators. Although many studies have solved the multi-objective problem by minimizing a single function comprising several subobjectives, this study employs the nondominated sorting genetic algorithm for the optimization of several objective functions. The present approach is tested with two example circuits from literature.

## 1. Introduction

The optimization of passive filters in distribution systems has been addressed through different approaches. In general, these can be classified as single-objective [1–15] and multi-objective [16–31] formulations.

The single-objective formulations normally try to determine the least costly filters that ensure compliance with the relevant power quality standards. In multi-objective approaches, other goals are added to achieve the following: the minimum total distortion of current [16,21,22,24,25,27,28,31], minimum total distortion of demand [18,21,22], minimum total distortion of voltage [18,21,22,27,28,31], minimum investment cost of filters [21,22,24,26–28], minimum cost losses [18,26], etc.

The reduction of the harmonic distortion indices of the supply current is a measure of the efficiency of the filters with respect to their capacity to absorb the harmonic distortion of the loads. In the case of the distribution system of an industrial-type customer, both the supply current distortion and voltage distortion at the point of common coupling must be confined to the recommended maximum limits.

However, a medium voltage primary distribution circuit supplies a large number of industrial, commercial, and residential customers that are sources of distorted currents to the circuit. All the nodes to which the customers are connected are points of common coupling between the primary distribution circuits and their customers. These customers are responsible for the injection of distorted currents in the medium voltage distribution circuit. The medium voltage distribution circuit is compliant with the standards for quality of voltage in all the nodes to offer a quality service to the clients. The reduction of the harmonic distortion indices of the voltages is a natural objective function in the optimization of the placement of harmonic passive filters in these circuits.

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* Corresponding author.
*E-mail addresses:* jandecycabral@hotmail.com (J. Cabral Leite), iperez@uclv.edu.cu, ignacioperezabril@gmail.com (I. Pérez Abril), manoelazevedo@yahoo.com.br (M.S. Santos Azevedo).

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In general, most studies consider the reactive power of filters at a fundamental frequency to be equal to a previously determined magnitude, and the optimization is devoted to calculate the other parameters of the filters that are required to minimize the distortion indices of the network.

In the present approach, the capacitor placement and passive filter placement problems are considered as a unified problem in which a set of passive compensators (capacitors and/or tuned filters) that allow to obtain the maximum annual saving in cost and maximum improvement of the power quality of the circuit are determined.

In this study, the annual saving is calculated as the equivalent present value of the compensation project to simultaneously account for the benefits of the reactive power compensation and the cost of investment in the compensators. The power quality indices considered are voltage magnitude and harmonic distortion indices of voltage as defined by the IEEE Std. 519 [32].

Although many studies have solved the multi-objective problem by minimizing a single function comprising several subobjectives, this study employs the nondominated sorting genetic algorithm (NSGA-II) for the optimization of several objective functions. The present approach is tested with two example circuits from literature.

## 2. Problem formulation

The present study addresses the capacitor and/or passive filter placement problem in distribution circuits contaminated by harmonic distortion. This multi-objective optimization problem is resolved by selecting and placing the required compensators to obtain (1) the maximum annual saving (*Saving*) of the compensation project, (2) minimum deviation of voltage ($\Delta V$), (3) minimum total harmonic distortion (THD) of voltage, or (4) the minimum individual harmonic distortion (IHD) of voltage. The solutions comply with the constraints of power quality and overstress of the capacitors

### 2.1. Independent variables

The independent variables of the problem, represented by the array $x$, are as follows: the number of compensators ($n$) and their placements ($u_1 \ldots u_n$), their control in time ($c_1 \ldots c_n$), the sizes of their capacitors ($Qc_1 \ldots Qc_n$), the tune frequencies ($f_1 \ldots f_n$), and the quality factors ($Q_1 \ldots Q_n$) of the filter-type compensators.

The possible placements are the nodes of the circuit. The control in time defines if the compensator is of fixed type ($c_i = 1$) or switched type (the compensator is connected in all the load states with index $\le c_i$). The sizes are multiples of the desired capacitor units.

The tune frequencies are selected from an array (*freq*) of possible tune frequencies for the harmonic passive filters. The variable $f_i$ can take the value zero, which implies that the compensator is a capacitor bank, or the compensator is a harmonic filter tuned to the frequency $freq(f_i)$. The tuned harmonic filters are not accurately tuned to the frequency of the harmonic $h$ to be eliminated; instead, these filters are tuned to a lower frequency of about $0.95\,h$. This practice enables to avoid the possible filter resonance with system impedance when there are variations in the filter parameters. Finally, the quality factors of filters are bound by $Q_i$ ($10 \le Q_i \le 100$).

### 2.2. Objective functions

Instead of presenting a closed formulation of the optimization problem, in this approach, we define four different objective functions that can be freely selected by the user to address the optimization problem.

#### 2.2.1. Annual saving of the compensation project

Considering a period of evaluation of $Y$ years with a reason of interest $i$, the annual saving obtained with the compensation project is calculated as follows:

$$Saving(x) = -I(x) / \sum_{k=1}^{Y} (1+i)^{-k} + C(0) - C(x) \tag{1}$$

where $I(x)$ is the cost of investment in the compensators, which is given by

$$I(x) = \sum_{i=1}^{n} (kc \cdot Qc_i + k_L \cdot QL_i + k_R \cdot PR_i) \tag{2}$$

where $kc$(\$/kvar), $k_L$(\$/kvar), and $k_R$(\$/kW) are the cost coefficients of the capacitors, inductors, and resistors of the compensators, respectively.

$C(0)$ represents the cost of the losses of the circuit in the base case (uncompensated), and $C(x)$ is the cost obtained after the installation in the network of the compensators, which is represented by $x$.

$$C(x) = c_{peak} \cdot \Delta P_{peak}(x) + \sum_{k=1}^{L} ce_k \Delta P_k(x) \cdot \Delta t_k \tag{3}$$

where $c_{peak}$(\$/kW) and $ce_k$(\$/kWh) are the corresponding cost coefficients for the peak power losses and the energy losses at the load level $k$.

To maximize the $Saving(x)$, the optimization requires the minimization of $-Saving(x)$.

#### 2.2.2. Maximum voltage deviation

The maximum deviation of voltage is defined as the difference between the maximum and minimum voltage for the set $U$ of all the system nodes and the set $L$ of all the load levels.

$$\max\ \Delta V(x) = \max_{\substack{k \in L \\ i \in U}} \left\{ V_{k,i}(x) \right\} - \min_{\substack{k \in L \\ i \in U}} \left\{ V_{k,i}(x) \right\} \tag{4}$$

By reducing the maximum deviation of voltage, the optimization process improves the voltage conditions in all system nodes and at all the load levels.

#### 2.2.3. Maximum distortion indices of voltage

Although there are potential problems with the use of capacitors in circuits contaminated by harmonic distortion, a compensation solution based on the use of capacitors that do not increase the indicators of distortion or even reduce them can be formulated. Moreover, the passive harmonic filters are specifically designed to reduce the voltage and current distortion indices.

Considering the set $U$ of the system nodes, set $L$ of all load states, and set $H$ of all harmonics present in the circuit, the maximum voltage distortion indices $THD$ and $IHD$ are defined as

$$\max\ THD(x) = \max_{\substack{k \in L \\ i \in U}} \left\{ THD_{k,i} = \sqrt{\sum_{h \in H} {V_{k,i,h}}^2} / V_{k,i,1} \right\} \tag{5}$$

$$\max\ IHD(x) = \max_{\substack{k \in L \\ i \in U \\ h \in H}} \left\{ IHD_{k,i,h} = V_{k,i,h} / V_{k,i,1} \right\} \tag{6}$$