Optimal location and dimensioning of capacitors in microgrids using a multicriteria decision algorithm

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ABSTRACT
This work presents a methodology for optimal compensation of reactive power in Electric Microgrids using a multicriteria decision algorithm based on heuristic methods. It was verified the optimal location and dimensioning of fixed capacitor banks in a microgrid with 14 buses with objective functions based on cost, efficiency and quality criteria in a maximum demand operating condition and also considering the constraints of objective variables in minimum demand scenarios. The proposed capacitance to be installed was considered as a discrete variable. The location of discretized reactive capacitances was simulated at candidate nodes analyzing the power flow in the case study, resulting in a wide solution space that was tackled by means of multicriteria optimization, using dominance elimination techniques and the weighted sum method for decision making. The variables analyzed were: cost, maximum and average deviations of the voltage profile, power factor, total losses in the lines of the system and THD. All these variables were also verified in minimum demand scenarios. The proposed solution provides significant improvements in the variables analyzed and verifies the optimal performance of the technique. The mathematical analysis demonstrates the need of addressing the reactive compensation problem by means of multicriteria decision and the proposal provides a very novel tool for calculating the location and dimensioning of reactive compensation devices in distribution systems and microgrids. The programming was done in the Matlab environment with simulations using Simulink. The case study analyzed is a very novel validated Microgrid system of which it is known the variables that take part of this analysis, as an approximation of the study of a very real Microgrid.

1. Introduction

The present paper takes part of a group of multidisciplinary research works whose objective is to improve, optimize, regulate, control and standardize future trends in the ambit of AC/DC HMGs in the implementation of the Smart Grid. Several authors conclude that the control and coordination of various MGs will be the most difficult challenge, however, in the ambit of HMGs the DG optimal placement strategies, compensation elements (dynamic and static) [1, 2, 3, 4, 5]; dynamic identification and mathematical modeling strategies [6, 7, 8, 9, 10, 11]; failure detection and identification strategies (FDI) [12, 13, 14, 15] and fault tolerant methodologies [16, 17, 18, 19, 20, 21, 22] are, undoubtedly, research fields where there is still much to do and investigate.

Conventional power systems may experience undesirable operating conditions when some of its nodes have voltages out of the band close to nominal values [23], harmonic distortion rates above standards, a power factor under unity or high level of losses, causing that efficiency and power quality in the network is reduced [24]. The operation of the microgrid at the maximum demand point or at the minimum demand point, either if it is connected or not to the grid, should also fulfill the aforementioned criteria.

A classic strategy to operate a conventional electric power system with quality and efficiently has involved using reactive compensation, by means of the optimal location and dimensioning of devices for reactive power compensation in particular buses. These compensators may improve the voltage profiles in the electric system, guaranteeing its operation around 1 in per unit, minimizing active and reactive power losses in the system, as well as improving the power factor in some buses and consequently the power factor in the entire system. However, the search for a solution that enables improving these variables may result in an undesired performance of the system with respect to other variables, which is demonstrated in [24].

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In many previous publications about proposals for optimal compensation of reactive power, most of the authors consider reduced objectives and mathematical constraints that provide an apparently good solution since they do not take into account the variables that may show conflict with the objectives pursued [24, 25]. This problem is due, to a large extent, to the case studies proposed by the authors for this analysis, where the majority of those case studies are validated in test distribution systems that do not consider distributed resources, with unknown data about other variables and that do not consider unbalanced loads which show high losses due to this issue [26]. Other problem is that previous research works only consider maximum demand scenarios, under the worst conditions of voltage and losses in the system, however, it is not verified how this proposed compensation result would perform in a minimum demand scenario, where the voltage profiles may exceed the maximum limits in some buses. It is very important to analyze the demand with the voltage profile [27], because these variables have an indirect relationship [27]. For this reason, this research is conducted on a more complex and real case study, in which all variables that have influence on the quality and efficiency of the electric system and the data of the load (balanced and unbalanced, single-phase and three-phase, linear and nonlinear, direct and alternate) in maximum and minimum demand scenarios are known [28]. The problem described defines the need of this research to consider a more real situation involving a wider group of variables that results in a decision making about compensation using multiple criteria.

As this work continues with the research of two previous publications [24, 28], it is stated the optimal compensation of reactive power in a microgrid by means of capacitor banks. Many research areas have formulated the problem of reactive compensation as an optimization problem with a single objective function. However, it is known that improving the voltage profile may have influence on the remaining variables that determine the power quality in an electric system [24]. Therefore, in order to decide about the capacitance and dimensioning of this compensation, as well as its cost, it may be simultaneously considered the voltage profiles, active power losses, global power factor and harmonic distortion rate in different scenarios and under the typical operating conditions of a microgrid. The objective is to decide which arrangement of capacitor banks attains the described operation of a microgrid with the smallest reactive power. For this purpose, it is established a formulation of the optimization problem that simultaneously considers the indicated variables that have influence on the quality and efficiency of the operation of a microgrid already modeled in the cited publication [28]. Therefore, it is an optimization problem involving various criteria, which implies a multicriteria decision statement. The algorithm defines its calculations considering maximum and minimum demand scenarios, calculating power flows through simulations with discretized compensation based on an Exhaustive Search algorithm that considers the location of discrete capacitances in the entire space of candidate buses. With the matrix of the results obtained, a second multicriteria decision algorithm is developed that weights each variable all of which were mathematically adapted to a minimization criterion, such that each compensation scenario (columns of the matrix) will have a unique weighted solution. Many solutions are eliminated due to the dominance criterion, and it is established a comparison that defines the optimal solution according to the group of criteria. With this novel methodology it is guaranteed that the proposed compensation solution really corresponds to a correct operation result of the system under analysis, this model and study significantly contributes to the scientific knowledge in the analysis of reactive power compensation in distribution systems with distributed resources. Within this research work, it is also analyzed a case where it is not considered the THD as objective criterion and with the result obtained it may be verified the conflict between the analysis variables in the system under study; this result justifies and supports the proposed methodology [25].

The present work is organized as follows. Section 2 presents Reactive compensations in Microgrids. Section 3 introduces the Methodology. Section 4 presents the Case Study. Section 5 includes the Simulation analysis of the proposed model. Section 6 shows the Future Works and Research Areas. Finally, conclusions are shown in section 7.

2. Reactive power compensations in microgrids

2.1. Hybrid AC/DC microgrid

In recent years, the configurations of Hybrid AC/DC Microgrids (HMG) are becoming a topic of great interest for the scientific and academic community. These combine the different advantages from MG architectures in AC and DC [28, 29]. A typical structure for an HMG is shown in Figure 1, where it can be seen the AC and DC topologies combined with each other, and different distributed generation (DG) devices or units. One of the main remarkable features of an HMG is its composition or structure, constituted by one MG in AC and another in DC, both combined in a single active distribution network. This configuration facilitates the direct integration (with all its benefits) of the DG sources, energy saving systems (ESS), controllable and noncontrollable loads in AC and DC. In addition, these features provide an excellent integration to the current distribution network or Smart Grid of DG units and electric vehicles (EV), without requiring large modifications [28, 29].

![Figure 1. Hybrid AC/DC Microgrid configuration.](image-url)
The DG sources constituted by new energy sources, are easily divided in two big groups: renewable and nonrenewable. Renewable energies, such as microturbines (MT), photovoltaic systems (PV), fuel cells (FC), wind generators (WG), have a technology which is more efficient, cleaner and capable of fulfilling the increasing electricity demand [30, 31, 32, 33, 34, 35]. The HMGs should be robust to control voltage, frequency, active power (P) and reactive power (Q), and also protect the main grid and the connected loads against the different faults to which they are exposed [15, 36]. Some authors consider MGs as a type of Smart Grid at small-scale that provide one of the most interesting solutions to improve power flow in distribution networks, reduce power losses in transmission lines, facilitate management and resynchronization from the demand side [3, 6, 37, 38].

An HMG may be integrated to a medium voltage (MV) distribution network or to a low voltage (LV) residential environment [28]. However, despite the new studies conducted in which they are analyzed and its favorable architecture in maximum and minimum demand scenarios, it is important to complement them with reactive compensation devices, both static and dynamic. This is one of the factors that needs to be improved, accompanied by reliability analysis, efficiency, device cost, among others.

2.2. Reactive power compensation

The reactive compensation problem is known from the beginnings of electrical power systems. There are various methodologies proposed to determine the location of a capacitor bank and to calculate the power of the bank to fulfill the required quality conditions. The use of optimization algorithms enables proposing the bank with the lowest reactive power and at the best location within the electric system. This problem also extends to microgrids [1, 39, 40]. The most commonly used improvements in distribution systems to compensate for reactive power is the installation of capacitor banks. It is a simple and low-cost solution to inject reactive power when it is required. Other authors also propose as a measure for reactive power compensation the adjustment of the capacitances of the transformers, since this a very inductive machine and has high consumption of reactive power [2] .

As an analogy to the case of a traditional electric system, it is about locating the suitable bus for inserting a compensation bank with the smallest reactive power to achieve power quality conditions. It is important to consider maximum and minimum demand scenarios, since a candidate solution that is valid for operating in the maximum demand scenario isolated from the main grid might not be valid in the minimum demand scenario isolated from the grid, if it violates some of the power quality conditions considered in the microgrid.

As part of the exhaustive search multiobjective algorithm, it is predetermined a set of values of reactive power (candidates), as well as a set of buses (candidates) for connecting the bank. However, the selection of a capacitor that injects a discrete amount of reactive power in a bus might not be the suitable choice. This is because a larger or smaller value of reactive power would offer a better power quality. Such value of reactive power would not have been considered in the vector of values of reactive power considered as candidates. This means that only discrete and commercial capacitive values will be considered, results with continuous capacitive values will not be considered.

There are other proposals of reactive compensation for electric power systems such as the SVC (Static Var Compensator), based on thyristors that regulate the conduction time in coils or capacitors (Thyristor Controlled Reactor, TCR, and Thyristor Switched Capacitors, TSC) [41]. Another solution is compensating by means of converters that base their operation in static switches such as the IGBT. This is the case of the STATCOM (Static Synchronous Compensator), where the injection of reactive power is also carried out in a non-discretized way [42]. These proposals are based on the operation of power electronics equipment. In the case of the SVC, the operation of thyristors injects harmonics additional to the fundamental, and thus it may be necessary to add filters [43, 44]. For the STATCOM, its control systems may be more complex, and thus this application may be justified when control speed is an essential variable [41].

2.3. Multicriteria algorithms

The reactive compensation optimization problems in electric power systems have been mainly analyzed as a single objective problem, that searches for an “optimal” solution with a unique criterion for dimensioning and locating devices for reactive power compensation. However, in this problem there are multiple variables involved in the decision criteria to really propose a good general solution in efficiency and power quality issues [45, 46]. The search for a solution focused on the improvement of a single variable might yield results with conflicts between the solution variables in the power flows. For this analysis, it is considered the objective as a linear combination of multiple variables. These variables would be: minimize investment costs, reduce power losses, improve power factor, reduce maximum and average deviations of voltage profiles and minimize total harmonic distortion in the voltage. All these mentioned variables will establish decision criteria in the analysis of maximum power demand and will also meet constraints for the operating limits of the system in minimum demand scenarios, where the analyzed variables may be affected by an excess of reactive power injected in a fixed compensation.

The multicriteria decision algorithm makes reference to the analysis of a set of n decision variables in a distribution system with a set of k objective functions with decision weight, and a set of e constraints. This may expressed in general terms as [24]:

\[
U(x) = [F_1(x), F_2(x), \ldots, F_k(x)]
\]

(1)

\[
e(x) = [e_1(x), e_2(x), \ldots, e_s(x)] \geq 0
\]

(2)

\[
x = [x_1, x_2, \ldots, x_n] \in X
\]

(3)

\[
y = [y_1, y_2, \ldots, y_k] \in Y
\]

(4)

Where:
- \(x\) is known as decision vector.
- \(y\) is the objective vector.
- \(X\) denotes the feasible decision space.
- \(Y\) denotes the objective space.

In this specific case, the objective of the optimization problem will be to minimize the criteria as a function of the desired objectives, despite adjustments performed in the mathematical ways of expressing the objective so that all may be considered with this minimum criterion. The set of constraints \(e(x) \geq 0\) determines the set of feasible solutions for \(X\), and the set of vectors of feasible objectives for \(Y\). From this, it may be deduced that the set of solutions produces an objective vector \(y\), where all the \(x\) must meet the set of constraints \(e(x) \geq 0\). The optimization problem consists in finding the \(x\) that has the “best” \(F(x)\). For determining the best decision, it is performed a reduction of the solution space by means of the elimination of solutions according to the dominance criterion. Afterwards, comparative searches are performed that define the minimum weighted value of the reduced solution space.

3. Methodology

The multicriteria optimization technique is applied to the set of solutions obtained for each analysis variable as solution of the power flows obtained in each scenario considered, based on the theory of decision makers. The algorithm assigns a particular compensation capacitance in one of the nodes that are candidates for the analysis, and with this injection of reactive power the power flows are recalculated obtaining a result for each objective variable. This process is iterative.
and is repeated until completing all proposed capacitances (discrete vector) in each of the nodes that are candidate for compensation. The Exhaustive Search algorithm (Brute Force) is justified in this analysis due to its precision, because it considers the entire set of feasible solutions and because the search space is relatively small (14 different capacitances to be installed in 6 candidate nodes, for a total of 84 iterations, number that defines the length of the decision matrix columns). In addition, it is a problem of future planning of the compensation where the computation times are not very demanding. The nodes considered as candidates are purely load nodes, that do not have any source of reactive power injection. The discrete vector of proposed capacitances to be installed is defined in steps of 50 kvar, from 50 kvar to 700 kvar which would be the maximum consumption of reactive power in this system.

Cost \( = \sum_{i=1}^{n} C_{Q_i} \geq 0 \) (5)  

Cost of installation of the reactive power, considering that \( C = $25 \text{hykvar} \) [47].

50 \( \leq |Q_i| \leq 700 \text{kvar} \) (6)  

Discrete vector of capacitances to be installed, in steps of 50 kvar.

As additional constraints to the problem it is considered that all nodes are equal candidates for the connection and that no node demands a different cost for the installation of the compensation devices. In addition, the load is modeled as a constant power load and the analysis is considered for maximum demand verifying the fulfillment of the limits of all the variables in the minimum demand scenario. The variables calculated and verified in each demand scenario, besides the cost, are:

\[
P_{\text{min}} = \sum_{i=1}^{n} (P_{gi}) - \sum_{i=1}^{n} (P_{ci}) \geq 0
\] (7)

Where, \( P_{gi} \) is the active power generated at node \( i \), \( P_{ci} \) is the active power demanded by node \( i \) by each load connected, and \( P_{\text{min}} \) are the total losses of active power in the microgrid. \( P_{gi} \), \( P_{ci} \) and \( P_{\text{min}} \) are given in kW.

\[
\varphi = \tan^{-1} \left( \frac{\sum_{i=1}^{n} Q_{ci}}{\sum_{i=1}^{n} P_{ci}} \right)
\] (8)

Where, \( \varphi \) is the microgrid power factor angle measured in the bus where it is coupled to the system, \( P_{ci} \) is the active power (in kW) demanded by each load in node \( i \) and \( Q_{ci} \) is the reactive power (in kvar) demanded by each load in node \( i \).

\[
\text{DPV} = \frac{\sum_{i=1}^{n} |V_{in} - V_{i}|}{n}
\] (9)

Average deviation of the voltage in the Microgrid, where \( n \) is the number of nodes of the System and \( V_{i} \) is the voltage in bus \( i \) in P.U. (per unit).

\[
\text{DMV} = \max_{i \leq n} |V_{i} - V_{in}|
\] (10)

Maximum deviation of the voltage, where \( n \) is the number of nodes of the System, \( V_{i} \) is the voltage in bus \( i \) in P.U. (per unit), and \( V_{in} \) is the desired voltage in bus \( i \) in P.U.

\[
\text{THD}_{\%} = 100 \frac{\sum_{i=1}^{n} V_{i}, h}{V_{i, 1}}
\] (11)

Total harmonic distortion index, where \( V_{i}, h \) is the voltage component corresponding to harmonic \( h \) at node \( i \), \( V_{i, 1} \) is the fundamental component of the voltage (1st harmonic) at node \( i \), \( h \) is the maximum harmonic order to be considered in the calculation.

As constraints to the problem, it is discarded solutions that at maximum or minimum demand do not meet the following limits:

\[
0.95 \leq V_{i} \geq 1.05
\] (12)

\[
\text{THDV m}ax \leq 5\%
\] (13)

In order to be able to obtain a result according to the dimensioning and location of the compensating device, it is necessary to establish the decision matrix. The \( n \) columns of this decision matrix show the eligible alternatives of all the analyzed compensation options that meet the criteria of being different, exclusive and exhaustive and which define the different dimensioning and locations of the compensating devices at the different nodes of the system and the \( m \) rows show the quantitative criteria that are defined by the variables analyzed as objective functions. According to the established decision criteria, it is selected the optimal option discarding at first instance all solutions that are lower than any other by means of the dominance criterion applied in the algorithm. In addition, all solutions where at least one of the criteria does not meet the constraints established as limits for these variables, which were defined previously, are eliminated.

The solution to this optimization problem consists in finding the best vector \( X \) within the set of eligible options, determined by the decision criteria established by the objective vectors. The results of each criterion in each alternative may be normalized using normalization statistical methods, in this case it is proposed the range normalization (method of the minimum and maximum (MM) value) as shown in (14).

\[
X_{\text{Norm}} = \frac{X_{i} - X_{\min}}{X_{\max} - X_{\min}}
\] (14)

The CRITIC method [48] is proposed for selecting the winning alternative in the decision matrix, based on the weighted sums of the criteria for each alternative. The CRITIC method defines a valuation to establish weights to each of the decision criteria (variables) and may be calculated as shown in (15).

\[
W_i = S_i \sum_{j=1}^{m} (1 - r_{ij})
\] (15)

Where:

- \( W_i \) is the weight of criterion \( i \).
- \( S_i \) is the standard deviation of the data of alternatives to criterion \( i \).
- \( r_{ij} \) is the correlation coefficient between row \( i \) and column \( j \).

The solution vector chosen as optimal shows the winning alternative defined by a location and dimensioning of the compensating devices that determine a new optimal distribution of the reactive power flows such that it is achieved a combined improvement of the variables analyzed. The selection of the dimensioning of the compensating devices is proposed as a discrete variable with the real nominal capacitances as a function of the type of device selected for the study. \( C = [50 \text{kvar} 100 \text{kvar} 150 \text{kvar} ... 700 \text{kvar}] \).

At last, the decision vector is obtained by means of the weighted sums of each alternative, which is achieved multiplying the result of each criterion within an alternative by the weight of that criterion and then adding up these results. Since all criteria are variables to minimize, it will be chosen as the winning alternative the one that has the minimum value in the resulting vector of weighted sums, this calculation is shown in (16).

\[
P_{\text{ond}} = \sum_{i=1}^{n} \sum_{j=1}^{m} W_{ij} X_{ij}
\] (16)

Moreover, an additional calculation tool is proposed in the algorithm where the user may define a weight for each variable and that the decision is conditioned to this choice defined by human intervention if it is preferred.

The proposed multicriteria optimization method will be resolved within the algorithm for solving the power flows in the systems under study, seeking to analyze the power flow solution variables in different scenarios, with the additional calculation of quality and efficiency.
variables that are stated as objective functions to be minimized. For this reason, the optimal solution of reactive power compensation studies depends on the calculation of the power flow and its analyzed variables with great accuracy. In this study, the power flows are calculated using iterative methods based on Kirchhoff laws in the Matlab-Simulink simulation environment. Figure 2 shows a visual representation of the objective of this research work.

4. System under analysis

4.1. Multicriteria algorithm

For applying this technique, it should be precisely determined the decision criteria and its scales in quantifiable measures. It should be evaluated the alternatives with their weight for each criterion, either qualitative or quantitative, for constructing the eligible set. As the last step, it is established the decision matrix to choose the optimal solution, as explained in the proposed methodology. Since it is a relatively small system, an Exhaustive Search algorithm will be implemented in this case study. After obtaining the decision matrix, the solutions will be analyzed by dominance, eliminating all solutions that are worse than any other solution in all their variables. For the multicriteria decision of the best location and dimensioning alternative of the compensating devices, it is used the weighted sums technique considering weights for each of the variables. Table 1 shows the description of the variables used in the implemented brute force Algorithm 1.

Table 2 contains the description of the variables used in the implemented brute force Algorithm 2.

Hereunder, the algorithms implemented for solving the multicriteria problem of reactive power compensation are detailed. Algorithm 1 details the problem of allocation by means of the exhaustive search technique, while algorithm 2 describes the multicriteria decision technique, as explained in the proposed methodology.

Algorithm 1: Improved brute force for the \( n \) buses.

Step 1 \( \text{Input:} \) \((n, \text{Candidate}_\text{bus}, \text{Capacitor}) \in \mathbb{N} \);

Step 2 \( \text{Output:} \) \((PF_{abc_n}, \text{PCC}, \text{Power}_{Loss}, \text{Total}_n, \text{DPVS}_n, \text{DVmax}_n) \in \mathbb{R} \);

Step 3 \( \text{Initialize:} \) \(\text{Capacitor} = [100e3:100e3:2000e3]; \) \(\text{Comp}_6 = 0; \) \(\text{Comp}_9 = 0; \) \(\text{Comp}_n = 0; \) \(\text{Phase} = 3; \)

Step 4 \( \text{For all} \) \( i = 1 \) \( \text{until} \) \( \text{Candidate}_\text{bus} \)

If \( i = 1 \) then

\( n = 6; \)

\( \text{Comp}_i = 1; \) \( \text{Comp}_{i+1} \) \( \text{until} \) \( \text{Comp}_n = 0; \)

Step 5 \( \text{For all} \) \( j = 1 \) \( \text{until} \) \( \text{size} \) \((\text{Capacitor}) \)

\( Qc_{\text{Cap}} = \text{Capacitor}(j); \)

Figure 2. Optimal location algorithm.
Table 2. Variables of algorithm II.

| Symbol | Variable |
|--------|----------|
| win_case | Winning case |
| N | Number of observations |
| DPVS | Average deviation of system voltage |
| DVmax | Maximum deviation of system voltage |
| Power_Losse_Total | Total losses of active power |
| angle | Power factor angle |
| THDV | Total harmonic distortion of the system |
| Cost | Costs of reactive power compensation |
| DPVS_Pond | Weight of the average voltage deviation |
| DVmax_Pond | Weight of the maximum voltage deviation |
| Power_Losse_Total_Pond | Weight of the total losses in the system |
| angle_Pond | Weight of the power factor angle |
| THDV_Pond | Weight of the Total Harmonic Distortion |
| Cost_Pond | Weight of the compensation cost |

Algorithm 2: Decision algorithm.

Step 1 Input: \( Voltage_{LL,pu,abc,n}; PF_{abc,n,PCC}; Power_{-Losses,Total,n} \) \( PF_{abc,1,PCC} \); \( PF_{abc,2,PCC} \); ... \( PF_{abc,n,PCC} \);

Step 2 Output: \( win_case \) \( Z \);

Step 3 Initialize: \( Cost = \{1:50:700\} \times 25; \) \( DPVS_{Pond} = 0.2; \) \( DVmax_{Pond} = 0.4; \) \( Power_{-Losses,Total_Pond} = 0.7; \) \( angle_{Pond} = 1; \) \( THDV_{Pond} = 1; \) \( Cost_Pond = 1.2; \) \( cont = 0 \);

\( A = [DPVS_1, DPVS_2, \ldots, DPVS_n-2, DPVS_n, DVmax_1, DVmax_2, \ldots, DVmax_n-2, DVmax_n, Power_{-Losses,Total_1}, Power_{-Losses,Total_2}, \ldots, Power_{-Losses,Total,n-2}, Power_{-Losses,Total,n-1}; \)

\( Power_{-Losses,Total_1}, \) \( Power_{-Losses,Total_2}, \ldots, \)

\( Power_{-Losses,Total,n-2}, \)

\( Power_{-Losses,Total,n-1}; \)

\( acos(PF_{abc,1,PCC}), acos(PF_{abc,1,PCC}), \ldots, acos(PF_{abc,n-2,PCC}), acos(PF_{abc,n-1,PCC}), acos(PF_{abc,n,PCC}); \)

\( THDV_{abc,1,D}, THDV_{abc,2,D}, \ldots, \)

\( THDV_{abc,n-1,D}, THDV_{abc,n,D}; \)

\( Cost_Pond \) \( Cost \) \( Cost \) \( Cost \);

Step 4 For all \( u = 1 \) until dimension (coders) if \((1-A(2,u))<0.95 \) (Voltage Limit Constraint) \( A(:,u) = \{\}; \) (Undesired results are eliminated)

\( End for all; \)

Step 5 For all \( i = 1 \) until dimension \( (A(:,1)) \) for all \( j = 1 \) until dimension \( (A(:,1)) \) \( Normalized \) \( Matrix \) \( (j,:); \) Normalized Matrix Range \( (j,i) = (A(j,i) - \min (A(:,j))) / \max (A(:,j)) - \min (A(:,j)); \)

\( End for all; \)

Step 6 For all \( n = 1 \) until dimension \( (A(:,1)) \)

\( \sigma(n,:) = \sum_{1}^{N} Normalized_Matrix(n,:) - Normalized_Matrix \) \( \sigma(N); \)

\( End for all; \)

Step 7 \( R = corrcoef(Normalized_Matrix); \)

For all \( m = 1 \) until dimension \( (A(:,1)) \)

\( Weight = \sigma \bullet (1 - R(:,m)); \) \( End for all; \)

Normalized Weight \( = \{1/\sum_{1}^{N} (Weight) \} \times Weight; \)

\( Pond = [DPVS_{Pond}, DVmax_{Pond}, Power_{-Losses,Total_Pond}, angle_{Pond}, THDV_{Pond}, Cost_Pond]; \)

Normalized Weight \( = Pond \times 1/\sum_{1}^{N} (Pond); \)

Step 8 For all \( k = 1 \) until \( j \)

\( Weighted_Sums = Normalized_Matrix \_Range(k,:); \) \( \bullet \) \( Normalized \) \( Weight \) \( (k) \) \( + \) \( Cont \)

\( Cont \) \( = \) \( Weighted \) \( Sums; \) \( End for all; \)

Step 9 \( \text{win_case} = \min (Weighted_Sums); \)

\( [\text{row},\text{col}] = \text{find} (Weighted \_\text{Sums} == \text{win_case}); \)

\( DPVS_{op} = A(1,\text{col}); DVmax_{op} = A(2,\text{col}); \)

\( Power_{-Losses,Total_{op}} = A(3,\text{col}); PF_{op} = \text{cos} (A(4,\text{col}); \)

\( Cost_{op} = A(5,\text{col}); \)

Step 10 \( \text{Return: \{win_case,DPVS_{op},DVmax_{op},Power_{-Losses,Total_{op}},PF_{op},Cost_{op}}; \)

Table 3. Load data for the Microgrid System.

| Bus | Load | Load Type | Max.load (kVA) | Min.load (kVA) | PF | Unbalance |
|-----|------|-----------|---------------|----------------|----|-----------|
| LV2 | Load 2 | Unbalanced load | 40 | 12 | 0.9 | 13 |
| LV3 | Load 3 | Unbalanced load | 30 | 9 | 0.85 | 12.6 |
| LV4 | Load 4 | Linear load | 50 | 15 | 0.9 | 0 |
| MV9 | Load 9 | Non-linear load | 320 | 96 | 1 | 0 |
| MV10 | Load 10 | Linear load | 800 | 240 | 0.8 | 0 |
| MV11 | Load 11 | Linear load | 400 | 120 | 0.8 | 0 |
| MV12 | Load 12 | Linear load | 800 | 240 | 0.8 | 0 |
| MV14 | Load 14 | Linear load | 1600 | 480 | 0.8 | 0 |
| DC | DC load | - | 2 | 0.6 | 1 | - |

Table 4. Data for the nonlinear Load.

| Transformer | Nominal Power (kVA) | Voltage Ratio (HV/LV) | Rcc (pu) | Xcc (pu) |
|-------------|---------------------|-----------------------|--------|---------|
| T1 | 1500 Y | 1380/220 Y | 0.03 | 0.03 |
| T2 | 1500 Y | 1380/220 Y | 0.03 | 0.03 |
| T3 | 4000 Y | 6900/13800 D1 | 0.015 | 0.015 |
| TB | 55 D1 | 900/220 Y | 0.003 | 0.06 |
| TG | 3500 Y | 1380/2400 D1 | 0.015 | 0.015 |
| TV | 1000 Y | 1380/250 D1 | 0.0012 | 0.03 |
| TDCI-2 | 15 Y | 120/150 Y | 0.03 | 0.06 |

Table 5. Transformer ratings for the microgrid system.

| Transformer | Nominal Power (kVA) | Voltage Ratio (HV/LV) | Rcc (pu) | Xcc (pu) |
|-------------|---------------------|-----------------------|--------|---------|
| TDC1-2 | 15 Y | 1380/220 Y | 0.03 | 0.03 |
| TPV | 1000 Y | 1380/220 Y | 0.03 | 0.03 |
| TG | 3500 Y | 1380/2400 D1 | 0.015 | 0.015 |
| TV | 1000 Y | 1380/250 D1 | 0.0012 | 0.03 |
| TDCI-2 | 15 Y | 120/150 Y | 0.03 | 0.06 |

Table 6. Line data for the microgrid system.

| Line | Sending end | Receiving end | R (ohm) | X (ohm) | Distance (km) |
|------|-------------|---------------|--------|---------|---------------|
| 1 | LV1 | LV2 | 0.0297 | 0.016335 | 0.15 |
| 2 | LV1 | LV5 | 0.0396 | 0.02178 | 0.2 |
| 3 | LV2 | LV5 | 0.0297 | 0.016335 | 0.15 |
| 4 | LV2 | LV4 | 0.0792 | 0.04356 | 0.4 |
| 5 | LV4 | LV5 | 0.0792 | 0.04356 | 0.4 |
| 6 | LV2 | LV3 | 0.0792 | 0.04356 | 0.4 |
| 7 | LV3 | LV4 | 0.0198 | 0.01089 | 0.1 |
| 8 | MV7 | MV9 | 0.788 | 0.2336 | 2.0 |
| 9 | MV6 | MV11 | 2.364 | 0.7008 | 6.0 |
| 10 | MV6 | MV12 | 2.364 | 0.7008 | 6.0 |
| 11 | MV6 | MV13 | 1.182 | 0.3504 | 3.0 |
| 12 | MV10 | MV11 | 2.364 | 0.7008 | 6.0 |
| 13 | MV13 | MV14 | 1.182 | 0.3504 | 3.0 |
| 14 | MV9 | MV14 | 0.788 | 0.2336 | 2.0 |
Table 7. Load flow solution for maximum demand scenario.

| Bus   | Type        | Pg (kW) | Qg (kVAR) | Pl (kW) | Ql (kVAR) | Ptransf (kW) | Qtransf (kVAR) | V (pu) | δ (°) |
|-------|-------------|---------|-----------|---------|-----------|--------------|----------------|--------|-------|
| LV 1  | BESS        | 42.66   | 30.45     | -       | -         | -            | -              | 0.955  | -29.76|
| LV 2  | Transfer Bus| -       | -         | -       | -         | -            | -              | 0.931  | -30.76|
| LV 3  | Transfer Bus| -       | -         | 64.72   | 40.11     | 62.6         | 43.86          | 0.930  | -31.26|
| LV 4  | Transfer Bus| -       | -         | -       | -         | 120.66       | 84.6           | 0.953  | -31.5 |
| LV 5  | Transfer Bus| -       | -         | -       | -         | 34.73        | 58.77          | 0.951  | -31.25|
| MV 6  | Transfer Bus| -       | -         | -       | -         | 780          | 1095           | 0.966  | -30.31|
| MV 7  | Transfer Bus| -       | -         | -       | -         | 554.6        | 356.2          | 0.971  | -30.72|
| MV 8  | Diesel      | 690     | 450       | 0       | 0         | -            | -              | 0.975  | -60.84|
| MV 9  | Non-linear load| -       | -         | 327.3   | 38.23     | -            | -              | 0.966  | -30.67|
| MV 10 | -           | 0       | 0         | 572.4   | 427.2     | -            | -              | 0.94   | -29.81|
| MV 11 | -           | -       | -         | 290.28  | 217.71    | -            | -              | 0.953  | -30.01|
| MV 12 | -           | -       | -         | 586.2   | 439.8     | -            | -              | 0.957  | -30.11|
| MV 13 | Slack       | 1810.2  | 1665      | 0       | 0         | -            | -              | 0.974  | -30.66|
| MV 14 | Transfer Bus| -       | -         | 119.61  | 89.7      | 226.02       | 397.2          | 0.967  | -30.59|
| DC    | DC Bus      | -       | -         | -       | -         | 8            | 0              | 0.928  | 0     |

Table 8. Load flow solution for minimum demand scenario.

| Bus   | Type        | Pg (kW) | Qg (kVAR) | Pl (kW) | Ql (kVAR) | Ptransf (kW) | Qtransf (kVAR) | V (pu) | δ (°) |
|-------|-------------|---------|-----------|---------|-----------|--------------|----------------|--------|-------|
| LV 1  | BESS        | 27.6    | 15.75     | -       | -         | -            | -              | 0.9567 | -31.27|
| LV 2  | Transfer Bus| -       | -         | -       | -         | 12.64        | 5.77           | 0.959  | -31.28|
| LV 3  | Transfer Bus| -       | -         | 21.1    | 13.09     | 25.47        | 14.43          | 0.967  | -31.14|
| LV 4  | Transfer Bus| -       | -         | -       | -         | 50.3         | 25.74          | 0.979  | -31.14|
| LV 5  | Transfer Bus| -       | -         | -       | -         | 51           | 26.79          | 0.983  | -31.24|
| MV 6  | Transfer Bus| -       | -         | -       | -         | 471.2        | 346.1          | 0.980  | -30.31|
| MV 7  | Transfer Bus| -       | -         | -       | -         | 89           | 84.4           | 0.98   | -30.25|
| MV 8  | Diesel      | 150.1   | 49        | 0       | 0         | -            | -              | 0.98   | -60.23|
| MV 9  | Non-linear load| -       | -         | 110.2   | 0.69      | -            | -              | 0.98   | -30.28|
| MV 10 | -           | 0       | 0         | 183     | 135       | -            | -              | 0.97   | -30.15|
| MV 11 | -           | -       | -         | 92.1    | 69        | -            | -              | 0.97   | -30.21|
| MV 12 | -           | -       | -         | 184.8   | 138.6     | -            | -              | 0.98   | -30.24|
| MV 13 | Slack       | 91.8    | 74.1      | 0       | 0         | -            | -              | 0.99   | -30.39|
| MV 14 | Transfer Bus| -       | -         | 372     | 279       | 21.84        | 84.6           | 0.98   | -30.3 |
| DC    | DC Bus      | -       | -         | -       | -         | 0.975        | 0              | 0.985  | 0     |

Figure 3. System demand curve.
Figure 4. AC/DC HMG: Case study.

Figure 5. Normalized criteria for reactive power compensation scenarios.
Figure 6. Weighted sums for each reactive power compensation scenario.

Table 9. Results of the criteria with discretized compensation in bus 10.

| Variables                        | Kvar400_n10 | Kvar450_n10 | Kvar500_n10 | Kvar550_n10 | Kvar600_n10 | Kvar650_n10 | Kvar700_n10 |
|----------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Average voltage deviation (V)    | 0.0378046   | 0.037431539 | 0.037089258 | 0.036727167 | 0.03641193  | 0.03595721  | 0.035574895 | 0.03525263 |
| Maximum voltage deviation (V)    | 0.06710086  | 0.066838833 | 0.066599846 | 0.066331056 | 0.066098259 | 0.06576465  | 0.065493043 | 0.06524164 |
| Total power losses (W)           | 61.75270992 | 61.59851312 | 61.52750890 | 61.49155704 | 61.4907694  | 61.4987523  | 61.5385238  | 61.57391723 |
| Power factor angle               | 0.652557711 | 0.639924639 | 0.628348656 | 0.614407259 | 0.601835829 | 0.58696866  | 0.57391732  | 0.56028413 |
| THDv (%)                         | 2.610446196 | 2.467541385 | 2.411907557 | 2.376111098 | 2.376740016 | 2.41371436  | 2.466273938 | 2.46572393 |
| Installation costs ($)           | 8775        | 10025       | 11275       | 12525       | 13775       | 15025       | 16275       | 16275       |

Figure 7. Voltage profile in maximum demand, (a) base case study and (b) compensated case study.
5. Case study

The following case study [28, 49] is chosen for this research work, among many others that are available, because it is a case study very real and complete, which comprises the analysis of a microgrid of which many data of electrical variables are known. It presents real load scenarios that enable a very practical and true analysis for a case of reactive power compensation where there are conflicts between the analysis variables. This Microgrid has single-phase and three-phase loads, nonlinear loads and, it is also evidenced, unbalanced loads.

Table 3 contains data about the loads connected to the Microgrid, as well as its power factor and the unbalance percentages. All loads were modeled as constant impedance loads. There is a nonlinear load at bus 9, specifically a pulse-width modulated (PWM) three-phase rectifier, which operates at a commutation frequency of 4080 Hz, with a modulation index of 0.8 and a fixed angle at open-loop. The operation parameters of the nonlinear load are shown in Table 4.

The data corresponding to transformers and lines are available in Table 5 and Table 6. There is a total of 7 transformers and 14 distribution lines in the Microgrid. Among the 7 transformers, 2 are step-down transformers that connect the medium voltage grid with the low voltage one, other 3 step-down transformers enable the interface at low voltage with the distributed generation. A step-down transformer enables the connection to the CCP and another step-up transformer connects the Diesel generator to the medium voltage grid. Among the 14 distribution lines, 7 operate at medium voltage and the other 7 operate at low voltage. Finally, the power flow results in the maximum and minimum demand scenarios are presented in Table 7 and Table 8, respectively. It is shown the generation powers \((P_g, Q_g)\), the load powers \((P_l, Q_l)\), the powers transferred through the lines \((P_{transf}, Q_{transf})\), as well as the bus voltages in magnitude and angle.

Figure 3 shows the demand curve, whose peak occurs at 11h00, which coincides with the maximum solar radiation and hence with the maximum generation capacity from the solar panels. The curve has its peak at 11h00.
Table 11. Real power: generated (neg.) and consumed (pos.) between the original and the compensated system, in (kW).

| Bus | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Benchmark system | -14.19 | -13.84 | 20.78 | 40.24 | 11.50 | 260.77 | 185.39 | -229.96 | 109.12 | 189.89 | 96.80 | 195.44 | -603.83 | -75.33 |
| Compensated benchmark system | -14.31 | -13.91 | 21.00 | 40.77 | 11.54 | 264.77 | 176.39 | -221.26 | 108.88 | 192.92 | 98.35 | 197.62 | -617.68 | -66.88 |

minimum at 3h00, with a demand of 30% with respect to the maximum peak.

Figure 4 shows the one-line diagram of the Microgrid under study, showing the nodes with the potential location of the capacitors that are candidates for the discretized capacitive compensation. The buses which are candidates for the installation of capacitive compensation are all medium voltage load buses: buses 6, 9, 10, 11, 12 and 13. The capacitive compensation powers are multiples values of 50 kvar up to a maximum of 700 kvar, according to Eq. (6), based on the maximum consumption of reactive power of the loads in the minimum demand scenario (Table 8).

6. Simulation analysis of the proposed model

After applying the proposed methodology with the Exhaustive Search algorithm for the evaluation and simulation of power flows with the reactive capacitances connected at each node and with the Multicriteria decision algorithm for searching the optimal solution regarding the dimensioning and location of the capacitor bank in this microgrid, very novel results are obtained which will be analyzed in this section.

Figure 5 shows the normalized unit performance of the variables (criteria) for each of the 84 compensation scenarios (14 proposed capacitances to be connected at 6 candidate buses), by means of a range normalized matrix. From this analysis it can be verified behaviors in each variable which are very similar visually when similar reactive compensations are used, but in different buses. However, the results differ significantly according to the bus at which the reactive power compensation is connected.

With the normalized criteria matrix obtained for each of the compensation scenarios, it is proceeded to perform the weighted calculation as indicated in the methodology of the proposed model. For this purpose, the normalized unit criteria of each variable with its weight for each compensation scenario are added up, thus establishing a new vector which is called weighted sums and that contains the final weighted criterion for each compensation scenario. It may be verified in Figure 6 the

Figure 9. Analysis per bus and phase, in maximum demand scenario, (a) base case study, (b) compensated case study and (c) low and compensated voltage profile.
result of this vector of weighted sums and it may be seen in the same figure that the winning alternative (minimum value) corresponds to scenario 41 that is defined by a reactive capacitive compensation in which 650 kvar are installed in bus 10 of the microgrid under study. The x-axis shows the capacities and locations of the capacitor.

After knowing the multicriteria winning alternative (650 three-phase kvar in bus 10), it is proceeded to analyze the individual results of each of the variables verifying that all meet the operational limits (constraints) both in maximum and minimum demand load scenarios, despite that the individual results which did not meet the constraints were eliminated in the decision algorithm as shown in step 4 of such algorithm.

After the new run of the power flows with the proposed reactive capacitive compensation the results are the following. Table 9 shows the real results, by variable, for the larger values of proposed compensation at the winning bus (bus 10). With this numerical result it may be established additional comparison criteria.

Figure 7 shows a comparison between the voltage profiles of the case study in a maximum demand analysis, graphically indicating the voltage in each phase and in each bus, where it may be observed a significant improvement in the bus voltages. Therefore, it is guaranteed that the two analysis variables for the voltage profile, which were the maximum and average deviations of the voltage profile, are minimized to a large extent with the fixed compensation of reactive power that was proposed as the winning alternative.

It is clarified that bus 15 of this microgrid under study is a direct current bus whose voltage is not affected by the reactive power compensation. Data of average deviation of the voltage per phase are shown on the top of each voltage profile graphic, and with these values it may be established comparisons noting a decrease of these deviations in each of the phases due to the proposed compensation. It may be also verified that the average voltage in all buses is within the admissible operating limits for a distribution system with respect to its voltage levels.

These results of average voltage profile for the 14 buses of the system under study may be also numerically verified in Table 10, where it may be established a comparison between the base case and the compensated case of the microgrid, evidencing a significant improvement in the voltage of all buses with the compensation of 650 kvar in bus 10. Although the problem is not only focused on the objective of improving the voltage profile and minimizing the variables associated to this criterion (DPV and DMV), voltage results are very good and define a

Figure 10. Power losses per line in maximum demand, (a) base case study and (b) compensated case study.
significant improvement of this variable in the system. These results of average voltage profile for the 14 buses of the system under study may be also numerically verified in Table 10, where it may be established the comparison between the base case and the compensated case of the microgrid.

Figure 8 shows the balance of active powers for the microgrid under study, where a) verifies this balance of active powers in the base case study, while in b) it may be visualized the balance of active powers for the scenario compensated with 650 kvar in bus 10.

This result may be also verified in Table 11, which shows the active powers generated (negative) and consumed by the loads (positive) for the base case study and for the scenario of optimal compensation of reactive power, according to the multicriteria decision. It may be verified a significant reduction in the required generation powers in most of the generation buses.

Figure 9 shows the balance of active powers for the microgrid under study, where a) verifies this balance of active powers in the base case study, while in b) it may be visualized the balance of active powers for the scenario compensated with 650 kvar in bus 10. The generation and compensation reactive powers may be visualized as negative values. It is also shown the voltage profile for the base case and for the compensated case, where comparisons may be established in this variable for the compensated state. In bus 10 it is evidenced a reactive power compensation component that appears as a result of the new redistribution of reactive power flows.

Figure 10 shows the active power losses in the lines of the system under study in the maximum demand scenario. In a) it is shown the lines losses for maximum demand (base case), while in b) it may be verified the line losses in this same maximum demand scenario for the compensated case. It may be appreciated a significant minimization of the losses in the compensated case with respect to the base case, due to the minimization of flows of reactive currents from the grid. A minimization of the active power losses is also seen due to the compensation of 2.54 kw.

Figure 11 shows the power factor in each bus for the base case system and for the compensated system in the maximum demand scenario. Analyzing the figure, it may be seen a great improvement in the power factor values in each of the buses, especially in bus 10 in which the compensation was carried out. It is important to note that the worst condition of the power factor variable for the base case was not in bus 10 but in bus 5. Despite this, the algorithm decided to carry out the compensation in bus 10 due to the weighting component in the other analysis variables (criteria). It may be also noted, as the most important analysis for this variable, that the power factor in the bus which is connected to the grid (bus 13) is significantly improved from 0.74 to 0.83.

The power factor variable, seen in bus 13, was the measuring parameter and criterion for this variable in the system and it can be seen that this result is significantly good.

In Figure 12 it may be verified the behavior of the harmonic distortion for each bus of the system under study, in the maximum demand scenario. In a) it is shown the THD for the base case of the microgrid, while
in b) it is shown the THD per bus for the compensated case. In this analysis it may be seen a significant improvement of the harmonic distortion in the system for the compensated case. This result demonstrates the need to consider this variable in the optimization problem of reactive power flows. The result does not exceed 3.5% of harmonic distortion in any bus.

6.1. Analysis of results in minimum demand

As it was already explained in the proposed methodology, once the algorithm makes a decision about the reactive compensation in the system (location and dimensioning of the compensating devices), this winning alternative is simulated in their power flows in a minimum demand scenario considering the fixed compensation. In this new run of power flows, it is verified that all electric power quality variables are within the admissible limits. Besides the cost, the calculated and verified variables in each demand scenario are:

\[
P_{\text{loss max}} \geq P_{\text{loss mind}} \geq 0, \text{ Verification of active power losses.}
\]

\[
\varnothing \geq 0, \text{ Inductive consideration of the power factor}
\]

Where, \( \varnothing \) is the power factor angle of the microgrid measured in the bus where it is coupled to the system.

\[
DPV \leq 0.04, \text{ Average voltage deviation in the Microgrid (per unit).}
\]

\[
DMV \leq 0.05, \text{ Maximum voltage deviation (per unit).}
\]

\[
0.95 \leq \frac{V_i}{V_i} \geq 1.05, \text{ Limits for the voltage profile.}
\]

\[
\text{THD}_V \leq 5 \%, \text{ Index of total harmonic distortion of voltage in each bus i.}
\]

Hereunder, it will be graphically shown the results obtained with the proposed compensation (650 kvar in bus 10) in the minimum demand scenario of this microgrid with 14 buses as proposed case study. The results will be shown for the voltage profile as the variable of higher interest in the verification of its limits.

Figure 13 shows the voltage profile of the system keeping the fixed compensation of 650 kvar in bus 10, but in the minimum demand scenario.
It may be verified in this result that bus voltages have raised, however, they remain within the admissible limits by constraint.

6.2. Analysis case without considering THD as an objective criterion.

Figure 14 shows the weighted sums solution for each of the 84 reactive power compensation scenarios in an analysis with only 5 variables, without considering the THD as objective criterion within the multicriteria optimization. This analysis was performed with the objective of demonstrating the conflict that exists between the variables and obtaining possible optimal results which are not really optimal. It is evidenced a result which is “apparently” very good and very similar in its weighting to the winning alternative already shown and this result is obtained with a minimum compensation of 50 kvar in bus 9. However, this undesired result is due to the harmonic distortion in such bus with nonlinear loads, situation that creates a conflict with the THD variable.

This undesired result supports the problem stated in this research, making evident the need that the reactive power compensation is addressed as an optimization problem with multiple criteria where variables such as harmonic distortion are considered.

This conflict may be visualized in Figure 15 where it is performed a calculation independent of the THD for each compensation scenario in bus 9. This harmonic distortion profile of the system under study is analyzed comparatively with the Maximum Voltage Deviation variable, which is considered as an objective in this particular analysis of 5 objective functions. Figure 15 a) shows the THD variable for each of the 14 buses of the alternating current microgrid in each of the 14 compensation scenarios for bus 9, whereas in Figure 15 b) it is visualized the Maximum Voltage Deviation of the entire microgrid for each of the 14 compensation scenarios in bus 9.

This result considers a winning alternative with minimum compensation of 50 kvar in bus 9 because of a raise of the voltage profiles as a
result of the harmonic distortion in this bus due to the connection of nonlinear loads. This undesired result demonstrates the need of incorporating the THD variable with a weight in the decision on the multicriteria result, since the effect of the minimum value of maximum voltage deviation occurs due to the maximum total harmonic distortion.

Figure 16 shows the steady-state voltage waveform with compensation of 50 kvar in bus 9. It is evident the high distortion undergone by this voltage wave due to the components of the nonlinear loads in this same bus. This effect of the harmonic distortion on the voltage caused a multicriteria decision with an undesired winning alternative, since this scenario corresponded to a compensation with minimum cost and a minimum value of maximum voltage deviation due to the effect of the distortion of increasing the voltage peak value, with an installed capacitance with values close to the resonance frequency of the system.

6.3. Analysis of the voltage variable for an isolated microgrid scenario.

Figure 17 a) y b) show the Microgrid voltage profiles in maximum and minimum demand scenarios, respectively, for the Microgrid under study isolated from the distribution network and considering the proposed reactive power compensation. In the scenario, considered the most critical, it is verified a stable behavior of the voltage profiles with the proposed compensation.

6.4. Future work and research areas

In order to optimize the power flow, the shared used of energy and improve the reliability, novel papers have been proposed regarding the control and the shared use of hybrid distributed energy based on the grid [50]. These control schemes have great importance in the optimization of
the performance of the system in more complex operating scenarios due to the penetration of the GD in the HMG. The optimization methods where cost is the priority are more common and seem to be more effective/feasible since the final objective of all optimization schemes is to reduce the cost, however, during this paper it could be demonstrated a series of conflicts existing between the different variables of the AC/DC HMGs and that should be taken into account in the future for other applications whose main objective is the optimization.

There are compensators that admit a continuous regulation of reactive power, as a replacement of the discrete compensation stated as a solution in this work. Besides the synchronous generator, formerly used to inject reactive power to the grid, there are the compensation systems that operate with thyristors. The simplest and widely extended solution is the SVC, which combines thyristor controlled reactors (TCR) and thyristor switched capacitors (TSC). However, the SVCs may reduce power quality because they inject harmonics, which is compensated with the use of passive filters. It is an economic alternative to continuously regulate reactive power.

Another possibility is offered by the STATCOM because it is an equipment capable of compensating inductive and capacitive reactive power, and it can also reduce the harmonic content, although it undoubtedly is an option which is more expensive than the SVCs due to the complexity of the control system. It is known that its operation is not altered as the voltage profiles degrade and that it may help to prevent the collapse of voltage in large systems.

7. Conclusions

This research is conducted on a case study in which all variables that impact the quality and efficiency of the hybrid microgrid are known, which include unbalanced loads, nonlinear loads, in maximum and minimum demand scenarios [28]. It is stated the optimal compensation of reactive power in a microgrid using capacitor banks. Other studies have formulated reactive compensation as an optimization problem with a single objective function. However, improving the voltage profile may have influence on the remaining variables that determine power quality in an electric system. In order to decide about the capacitance, dimensioning and cost of the compensation, it may be simultaneously considered the voltage profile, active power losses, global power factor and harmonic distortion rate.

In this work it has been stated as an optimization problem with multicriteria decision. The algorithm considers the two demand scenarios, calculating the power flows with discretized compensation based on an Exhaustive Search algorithm with location of discretized capacitances in a space of candidate buses. With these preliminary results, it is developed a second algorithm that weighs each variable, adapted to a minimization criterion. Consequently, each compensation scenario has a weighted solution, after some have been discarded by the dominance criterion, to finally choose the optimal solution that meets the criteria. With this methodology it is guaranteed that the compensation solution responds to a correct operational result for reactive power compensation in distribution systems considering distributed resources. Within the research it is also analyzed a case where the THD is not considered as an objective criterion and with the result obtained it may be verified the conflict between the analysis variables in the system under study, result that justifies and supports the proposed methodology.

The proposed methodology provides very novel solutions that demonstrate the need that the problem of reactive power compensation is treated as a multicriteria problem and considering a larger number of quality and efficiency variables than the ones considered so far by different authors.

Declarations

Author contribution statement

Alexander Águila: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Leony Ortiz: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Rogelio Orizondo: Contributed reagents, materials, analysis tools or data; Wrote the paper.
Gabriel López: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data associated with this study has been deposited at Universidad Pontificia Bolivariana de Medellín.

Declaration of interests statement

The authors declare no conflict of interest.
