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Optimization Methods with Power Quality Issues for Reactive Power Control of Distribution Networks with Dispersed Generation

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Abstract — **The paper deals with the reactive power control in a MV distribution system in presence of Dispersed Generation (DG). The control variables are the reactive powers of DG units and capacitors, and the tap position of the on-load tap changer of the HV/MV transformer. Single-objective and multi-objective optimization problems are formulated and solved in order to achieve the optimal control, even containing the impact of the waveform distortions. Numerical applications performed on a 109-bus test distribution system give evidence of the effectiveness of the proposed procedure.**

Index Terms — **Reactive power, Power Quality, Dispersed Generation, Distribution systems, Single-objective optimization, Multi-objective optimization.**

I. INTRODUCTION

The deregulation of electricity generation and retailing introduces new paradigms to the planners and operators of electrical distribution systems. Special attention is required when dealing with ancillary services, such as the reactive power service, which are essential for the operation of the network, but can cause operators to incur not readily identifiable costs in their provision. On the other hand, the reactive power service has become of growing interest and complexity, due to the widespread presence in distribution systems of Dispersed Generation (DG) [1]-[9].

This paper deals with the optimal reactive power control in a distribution system with DG. The distribution system is characterized by the presence of capacitors and DG units, and is connected to a high voltage bus with an on load tap changer transformer (OLTC). For each electrical system state, the problem to be solved is to identify the control variable values (reactive powers of DG units and capacitors, and tap position of the OLTC) that minimize one or more objective functions subjected to proper equality and inequality constraints.

In the relevant literature, the problem of the optimal reactive power control in a distribution system with DG have been formulated as both single-objective (SO) and multi-objective (MO) optimization problem [1]-[8]. In particular, in this paper we refer to the proposals recently appeared in [1]-[3].

In [1] the regulating costs are included in the single objective function to be minimized; a unique optimal solution is provided that minimizes the sum of the costs sustained by the distributor for carrying out the reactive power service.

In [2], [3] a method based on multi-objective (MO) optimization is proposed for solving the problem; this method optimizes independently and simultaneously several objectives that take into account technical and economical aspects. The objective functions to be minimized are the active power losses, the average voltage deviations, the maximum voltage deviation, and the regulating costs.

However, the optimization models proposed in [1]-[3], such as others proposed in the relevant literature, do not consider that the widespread use of static converters in the electrical distribution systems causes waveform distortions whose levels are influenced by the presence of capacitors and DG units; in turn, voltage and current distortions can cause detrimental effects on these electrical components, as well as on all the distribution system components. In particular, the capacitors are among the most sensitive and critical components in respect to the waveform distortions: they can heavily affect the waveform distortion levels at all system buses, causing, in some cases, very dangerous resonance phenomena. On the other hand, as it is well known, several Standards require the control of the overload of the capacitors in presence of harmonics; for example, IEEE Standards limit the capacitor kVAr supplied at each bus, taking into account the harmonic contribution. In addition, the DG units influence differently this PQ disturbance if they are connected directly (e.g., synchronous generators) or with power electronic interfaces.

On this ground, the methodology of analysis discussed in this paper makes it possible to join the problems related to the management efficiency and those related to the Power Quality problems, leading to a conceptual widening of the Energy Management methodology applied to the distribution systems. In particular, the original contribution of this paper consists in reformulating the single-objective and multi-objective models

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proposed in [1]-[3], by taking into account the presence of the waveform distortions in both the objective functions and constraints. In practice, the optimization problems are reformulated considering a multi-converter distribution system in which DG units are connected directly or with power electronic interfaces.

Proper algorithms are applied to solve the optimization problems, taking into account that some control variables, such as the capacitor units and the OLTC tap position, are discrete variables.

Finally, the obtained solutions are compared and discussed with reference to a MV 109-bus test distribution system.

II. PROBLEM FORMULATION

Let us consider a typical medium voltage multi-converter electrical distribution system derived from a single HV bus and in presence of Dispersed Generation (DG), which can make use of reactive power control devices (HV/MV on load tap changer transformer, capacitor banks and DG synchronous generators).

In the following the single objective (SO) and multi-objective (MO) optimization problems proposed in [1]-[3] are properly reformulated, taking into account the presence of the waveform distortions in both the objective functions and constraints.

A. Single Objective optimization

The problem is formulated as a mixed non-linear constrained optimisation problem in which an objective function has to be minimized while meeting a number of *equality* and *inequality* constraints.

In particular, in this paper the SO problem is formulated as:

$$\min \ F_1(\boldsymbol{X},\boldsymbol{U}) \tag{1}$$

subject to:

$$\boldsymbol{g}(\boldsymbol{X},\boldsymbol{U}) = 0 \tag{2}$$

$$\boldsymbol{h}(\boldsymbol{X},\boldsymbol{U}) \le 0 , \tag{3}$$

where ***X*** is the system state vector, and ***U*** is the vector of the control variables that are:

Q_{DG}**:** vector of the reactive power of the N_g generators connected to the distribution system (continuous variables);

Q_{cap}: vector of the reactive power of the N_c capacitor banks (discrete variables); and

m: tap position of the OLTC (discrete variable).

The *objective function* to be minimized is the sum of all costs sustained by the distributors for carrying out the reactive power control [1]:

$$F_1 = \left(C_P P_L + C_{DG} Q_{DG} + C_{cap} Q_{cap} + C_{HV} Q_{HV} + P_P P_{harm} \right) \Delta T \tag{4}$$

where C_P is the active power price (\$/MWh), P_L represents the distribution system active power losses at the fundamental frequency (MW), C_{DG} is the DG reactive power price (\$/MVArh), Q_{DG} is the DG reactive power (MVAr), C_{cap} is the capacitor banks reactive power price (\$/MVArh), Q_{cap} is the capacitor banks reactive power (MVAr), C_{HV} is the price of the reactive power imported from the HV grid (\$/MVArh), Q_{HV} is the reactive power imported from the HV grid (MVAr), P_{harm} represents the distribution system active power losses due to the harmonics (MW), and ΔT is the regulating interval.

The cost C_{DG} is defined with respect to the synchronous generator capability curve, as shown in [1]. In particular, the cost is constant in the region where the reactive power variation doesn't imply a reduction of active power and it increases where the variation of reactive power produces a reduction of active power.

As for the *equality constraints*, the typical power flow equations at fundamental frequency are properly formulated to take into account the problem variables. In this regard, note that the reactive powers produced by the DGs and the capacitor banks are control variables and, hence, they are included in power flow balance equations. In addition, as above mentioned, the variation of the DG reactive power can imply a reduction of the active power produced by the same DG, and, hence, also this circumstance is taken into account in the power flow balance equations.

Besides the typical power flow equations at fundamental frequency, the following relationships at the harmonic frequencies are considered:

$$\bar{J}^h = \dot{Y}^h \ \bar{V}^h, \ h = H_{\min} \ldots H_{\max} , \tag{5}$$

where $\bar{J}^h, \dot{Y}^h, \bar{V}^h$ are the vectors of the currents injected in the buses, the admittance matrix and the vector of the bus voltages, respectively, all considered at the h^{th} harmonic order, and $H_{\min}$ and $H_{\max}$ are the minimum and maximum harmonic order.

The harmonic injections of non-linear devices are modeled according to the recommendations of the IEEE PES Working Group on Harmonics Modeling and Simulation [10], [11], where it is suggested to adjust the phase angles of the injected harmonic current sources according to the phase angle of the fundamental with respect to the reference.

The optimization model (1)-(3) also includes *inequality constraints*, both at the fundamental and at harmonic frequencies.

The *inequality constraints at the fundamental frequency* are used to ensure that the voltages of all network buses fall inside an admissible range that is:

$$V_{\min,i} \le V_i^1 \le V_{\max,i} \quad i = 1 \ldots n \tag{6}$$

where V_i^1 is the voltage magnitude at fundamental frequency for the i^{th} bus and n is the number of buses of the network, and that the reactive powers to be assigned to DG units are limited by the generation capability curves [1].

The *inequality constraints at harmonic frequencies* are included to limit the RMS voltages, the single harmonic voltages, the Total Voltage Harmonic Distortion Factor (THD_V), the total capacitor banks reactive power. That is:

$$k_1 \le \sqrt{\sum_{h=1}^{H_{\max}} \left(V_i^h\right)^2} \le k_2 \quad i=1...n,\ h=H_{\min},...,H_{\max}$$

$$V_i^h \le k_3{}^h \quad i=1...n,\ h=H_{\min},...,H_{\max}$$

$$\sqrt{\frac{\sum_{h=H_{\min}}^{H_{\max}} (V_i^h)^2}{(V_i^1)^2}} \le k_4 \quad i=1...n \tag{7}$$

$$\omega_0 C \sum_{h=1}^{H_{\max}} h(V_m^h)^2 \le k_5\ Q_r \quad m \in \Omega_{cap},$$

where $\omega_0 = 2\pi f_0$, Q_r, C are the fundamental angular frequency, the reactive power and the capacitance of the single capacitor bank, respectively[1].

Moreover, the constraints on the discrete nature of both capacitor sizes and transformer tap positions have to be considered.

It should be noted that the new formulation of the SO optimization problem (1) has the following additional features with respect to the formulation proposed in [1]:

(i) it includes the losses at harmonic frequencies in the objective function F_1;

(ii) it takes into account the network's linear harmonic equations (5) in the equality constraints;

(iii) it includes limits on the harmonic distortion indices (single voltage harmonics and total harmonic distortions) at each bus and on the overload of capacitors in the inequality constraints. Also limits on the overload of other system components can be easily included.

B. *Multi-Objective optimization*

The formulation of the MO problem is expressed by:

$$Min\ \left[F_1(\mathbf{X},\mathbf{U}), F_2(\mathbf{X},\mathbf{U}), F_3(\mathbf{X},\mathbf{U}), F_4(\mathbf{X},\mathbf{U}), F_5(\mathbf{X},\mathbf{U})\right] \tag{8}$$

subject to:

$$\boldsymbol{G}(\boldsymbol{X},\boldsymbol{U}) = 0$$
$$\boldsymbol{H}(\boldsymbol{X},\boldsymbol{U}) \le 0, \tag{9}$$

where the objective functions F_i (i = 1,…5) to be minimized are:

- the regulating costs F_1, already defined in (4);
- the active power losses at both fundamental and harmonic frequencies F_2, defined as:

$$F_2 = P_L + P_{harm}\,; \tag{10}$$

- the average voltage deviations F_3:

$$F_3 = \frac{\sum_{i=1}^{n} \left|V_i^1 - V_i^*\right|}{n}, \tag{11}$$

where V_i^* is the desired value of the voltage at bus *i*;

- the maximum voltage deviation F_4:

$$F_4 = \max_i \left|V_i^1 - V_i^*\right|; \tag{12}$$

- the mean value of the Total Voltage Harmonic Distortion factors (THD_V) at all system busbars F_5, already defined in (7).

The functions ***G*** are the equality constraints to be met: load flow equations and network's linear harmonic equations, already discussed in the previous section. The functions ***H*** are the inequality constraints which can include DG reactive power limits, bus voltages limits, limits on the harmonic distortion indices (single voltage harmonics and total harmonic distortions) at each bus and the overload of each system component (including capacitors and DG units); also line currents limits can be taken into account. Once again, the constraints on the discrete nature of capacitor sizes and transformer tap positions have to be considered.

It should be noted that the new formulation of the MO optimization problem (8) has the following additional features with respect to the formulation proposed in [2], [3]:

(i) it includes the losses at harmonic frequencies in the objective function F_1;

(ii) a further objective function (F_5) is added;

(iii) it takes into account the network's linear harmonic equations (5) in the equality constraints;

(iv) it includes limits on the harmonic distortion indices (single voltage harmonics and total harmonic distortions) at each bus and on the overload of each system component (including capacitors and DG units) in the inequality constraints.

III. PROBLEM SOLUTION

Several algorithms can be applied to solve SO and MO optimization problems. In the following subsections the algorithm applied in the numerical applications will be shown.

A. *Single Objective problem solution*

In this paper, the *SO problem* (1) is solved by using the two-steps algorithm proposed in [1], where the first step considers the problem variables as continuous variables and solves the problem with the Sequential Quadratic Programming (SQP) and the second step consists in a heuristic procedure aimed at assigning the permitted values to the discrete variables. The SO problem can be solved also with the well known genetic algorithms (GA), that can require high computational efforts. In the numerical application of this paper the GA is applied only to check the accuracy of the two-steps procedure.

B. *Multi-Objective problem solution*

Whereas traditional SO optimisation procedures give as a result a unique solution point, in *MO programming* a set of optimal solutions (non inferior solutions) is provided; the Decision Maker has to choose the solution from this set considering the relative importance of the conflicting objectives, and the final solution depends on his perspective. Several techniques are used for generating non-inferior solutions. Since this paper concentrates its interest on problem

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[1] Depending on the values of k_1, k_2, k_3^h and of the limits on the fundamental voltage V_{max} and V_{min}, the constraint (6) or the first of the (7) could be redundant.

formulation rather than on problem solution, the ε-constrained method has been used [12].

In any case, it has to be underlined that other high performing algorithms can be applied, such as the one proposed in [2].

In the ε-constrained technique, first a starting solution is carried out by solving a SO optimization problem. The objective function to be minimized is a linear combination of the objective functions above described, that is:

$$F(x)=\sum_{i=1}^{5} w_i F_i(x) \tag{13}$$

where $w_1,\dots,w_5 \in \Re^+$ are weighting coefficients, that define the relative importance of the objectives. The constraints are given by (9). The result of this optimization problem is defined as a global solution, F^*, whereas the single objective functions are $F_i^*, i=1,\dots,5$.

Starting from the global solution, one objective function is selected as master objective function, whereas the other objective functions (slave objective functions) are regarded as new constraints to be complied with.

The resulting problem can be formulated as:

$$\min F_k(\mathbf{X},\mathbf{U}) \tag{14}$$

subject to

$$\begin{aligned} &\boldsymbol{G}(\boldsymbol{X},\boldsymbol{U})=0\\ &\boldsymbol{H}(\boldsymbol{X},\boldsymbol{U})\le 0,\\ &F_j \le F_j^* + \Delta\varepsilon_j \quad j=1,\dots,5 \quad j\ne k, \end{aligned} \tag{15}$$

where $\Delta\varepsilon_j$ represents the admissible variation range of the j^{th} objective. It is worth noting that the Decision Maker can solve the optimization problems (14)-(15) considering all the objective functions as master functions and also for several values of $\Delta\varepsilon_j$.

IV. NUMERICAL APPLICATIONS

The reactive power control problems formulated in Sect. II have been solved with reference to a 109-nodes test system which is part of an actual, more extended, distribution system. The test system is shown in Fig. 1; the rated load powers are reported in Appendix. The network is fed by a 150/20 kV, 5

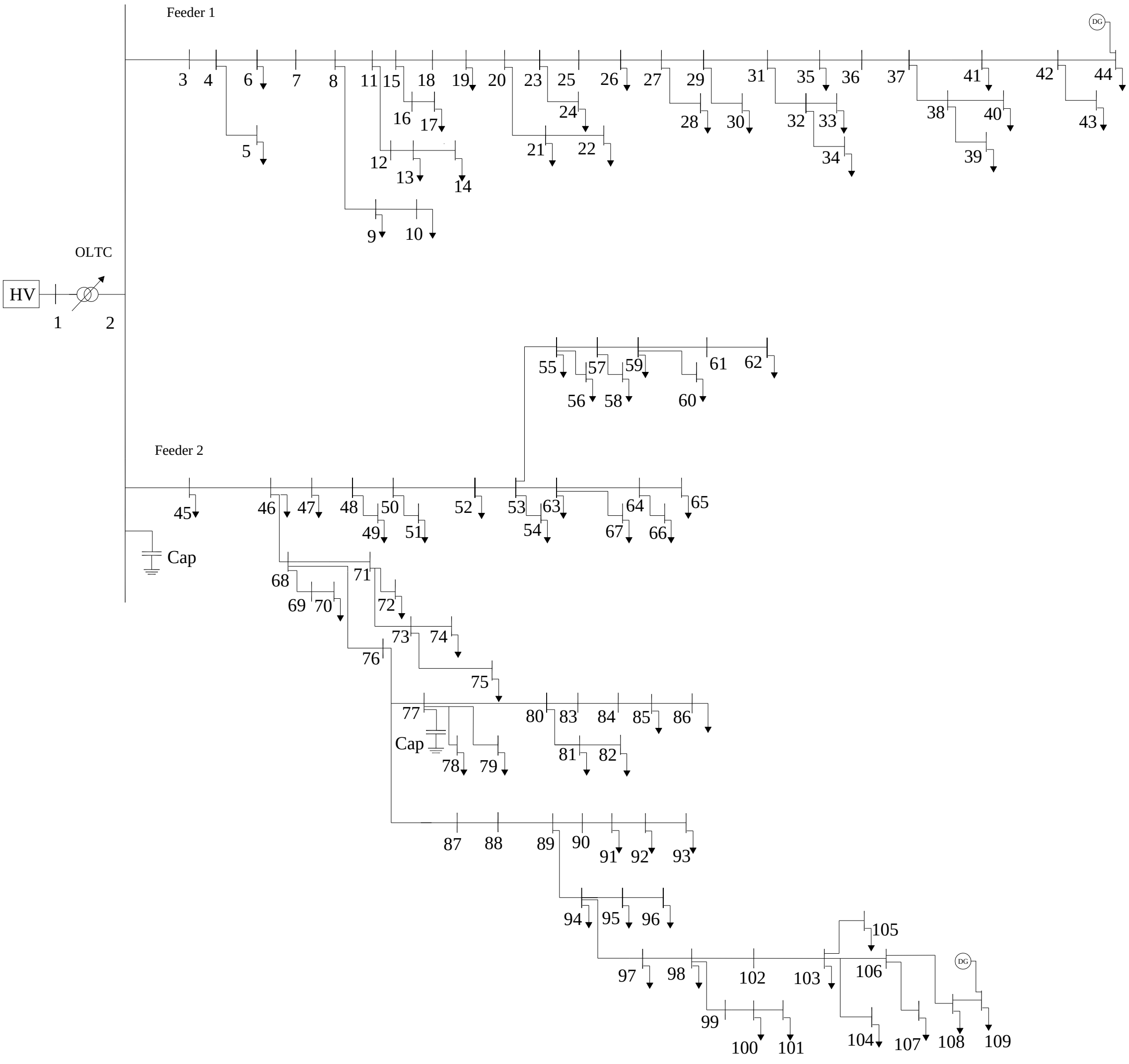


Fig. 1. The test distribution network.

MVA OLTC transformer with $V_{cc\%}$=8%. The tap positions of the OLTC can assume discrete values in the range ±5% of the nominal transformer ratio; the transformer has been modeled according to [13]. The HV three-phase short circuit is 7500 MVA. The DG units, located at buses #44 and #109, are synchronous generators which are connected to the system by means of 0.4/20 kV transformers with $V_{cc\%}$ = 4.5%. According to the typical capability curve of a synchronous generator, the reactive power furnished by the DG units is within the range of –0.2 to 0.2 MVAr, and the active power is up to 0.5 MW. The capacitor banks at buses #2 and #77 are assumed to come in discrete sizes of [0, 150, 300] kVAr. To stress the system in terms of waveform distortions, four six pulse AC/DC converters have been considered as sources of harmonics. The converters are connected to buses #43, #51, #67 and #96 (390, 404, 316 and 360 kW, respectively) and operate with a firing angle of 20°. In Tab. I the values of the optimization problem parameters (costs and limits) are reported. In particular, the price of the control variables for the voltage regulation are normalized respect to the price of 1 MWh (40$/MWh) [1]. Taking into account the values of k_1, k_2, k_3^h V_{min} and V_{max}, the first constraint of (7) results to be redundant.

TABLE I
COSTS AND LIMIT VALUES

Control variables price (pu)		Limits values (pu)	
C_{QHV}	0.003	k_1	0.9
C_{cap}	0.0022	k_2	1.1
C_{DG}	0.01	k_3^h	0.03
C_P	1	k_4	0.08
		k_5	1.35
		V_{min}	0.95
		V_{max}	1.05

In the next subsections, two case studies are analyzed: the first case involves the solution of the SO problem formulated in Sub-sect. II.A, and the second case concerns the solution of the MO problem formulated in Sub-sect. II.B.

A. Case Study 1

The typical daily load variation of Fig. 2 has been considered at each node. The load variation is expressed in p.u. of the rated load powers given in Appendix.

The SO problem has been solved for the test system of Fig. 1. Regarding the equality and inequality constraints, in order to evidence the influence of the waveform distortions, besides the power flow equations at fundamental frequency, firstly only the constraints at fundamental frequency have been taken into account, then also the PQ constraints (5) and (7) have been included. Figs. 3–5 show the hourly reactive power of the capacitor banks, of the DG units, and the reactive power imported from the HV network, respectively, with and without the PQ constraints.

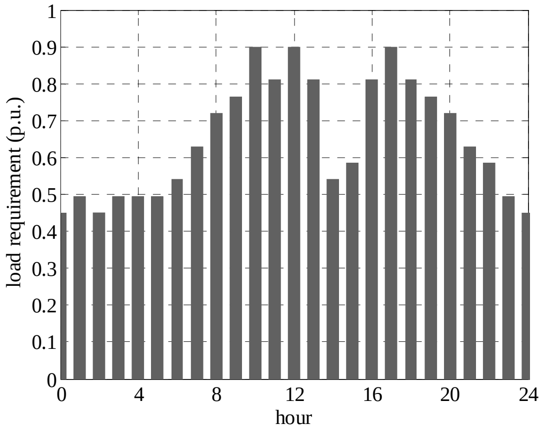
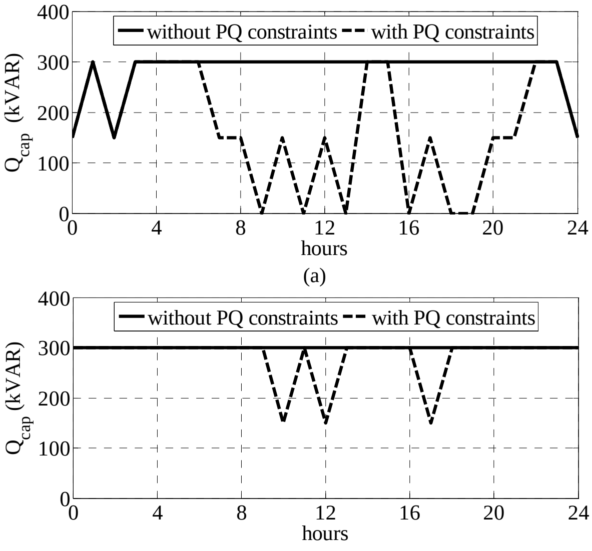


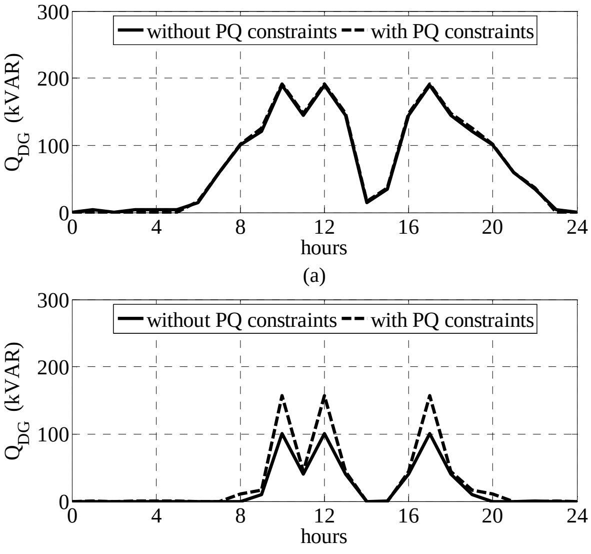
Fig. 2. Daily load variation



(a)

(b)

Fig. 3. Capacitor banks reactive power (Q_{cap}) at bus #2 (a) and at bus #77 (b), without and with PQ constraints



(a)

(b)

Fig. 4. DG reactive power (Q_{DG}) at bus #44 (a) and at bus #109 (b), without and with PQ constraints

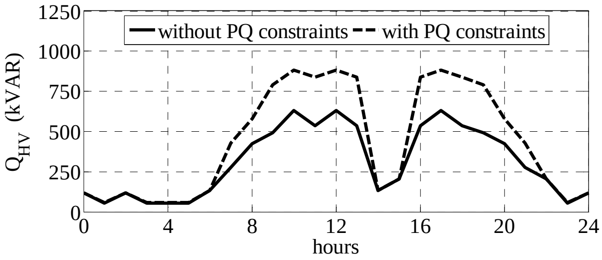
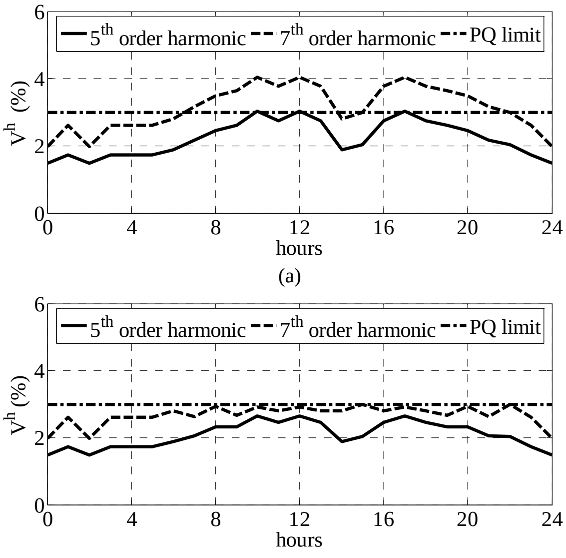


Fig. 5. Reactive power imported from the HV node (Q_{HV}), without and with PQ constraints

In addition, as an example, Fig. 6 shows the comparison of the hourly variation of 5th and 7th order harmonic voltages at bus #96 along with the PQ limit, with and without the PQ constraints.



(a)

(b)

Fig. 6. Harmonic voltages (V^h) at bus #96, without (a) and with (b) PQ constraints.

From the analysis of Figs. 3–5 it clearly appears that the PQ constraints influence the control variables for various values of the load requirements. Obviously, the objective function in the PQ constrained case assumes values greater than in the PQ unconstrained case. It should be noted that, as foreseeable, the capacitor banks are the main cause of modifying the magnitude of the harmonic voltages (Figs. 3 and 6). The reactive power injected by the DG unit at node #44 practically does not change when the PQ constraints are imposed. This is probably due to the fact that no capacitor banks are connected to the feeder's bus. The improvements of PQ levels when the harmonic constraints are taken into account and the influence of the control variable values are evident. The results shown in Figs 3–6 have been obtained by applying the two-steps algorithm proposed in [1]. In order to check the accuracy of this procedure, these results have been compared with the solutions obtained with the application of a GA. As an example, Tab. II shows the values of the control variables obtained applying the GA and the two-steps algorithm (TSA) for the load level corresponding to the peak value in Fig. 2.

TABLE II
GA AND TWO-STEPS ALGORITHM (TSA) RESULTS

Q_{cap} (kVAr)				Q_{HV} (kVAr)	
GA		TSA		GA	TSA
# 2	# 77	# 2	# 77	876	882
150	150	150	150		
Q_{DG} (kVAr)				OLTC tap position	
GA		TSA		GA	TSA
# 44	# 109	# 44	# 109	1.05	1.05
191.4	163.2	192	156.8		

The values of both objective function and control variables obtained applying the two algorithms are very similar. However, the GA is more time consuming than the two-steps algorithm. On the other hand, it should be noted that some convergence problems have been observed in the second step of the two-step algorithm, mainly with reference to the capacitor bank reactive power. In these cases, an exhaustive procedure has been applied to obtain the optimal solutions, with an unavoidable influence on the computational efforts.

B. Case Study 2

For the sake of conciseness, Tab. III shows only six alternatives obtained applying the ε-constrained technique shown in Sect. III-B to the MO optimization problem reported in Sect. II-B. The results refer to a single load level (corresponding to the peak load request of Fig. 2) and are obtained considering all the objective functions as master ones and also for different values of $\Delta\varepsilon_j$. For each alternative, the control variables values are reported.

TABLE III
ALTERNATIVES OBTAINED FOR A SINGLE LOAD LEVEL

Alternative	Q_{cap}#2 (kVAr)	Q_{cap}#77 (kVAr)	Q_{DG} #44 (kVAr)	Q_{DG} #109 (kVAr)	m
A_1	150	150	192.05	157.10	1.05
A_2	150	150	200	200	1.05
A_3	0	150	190.51	30.38	1.03
A_4	0	0	151.25	126.53	1.03
A_5	0	0	200	200	1.05
A_6	0	0	175.10	155.63	1.03

Tab. IV shows the values that the above-mentioned objective functions F_i (i=1,…5) assume for each alternative. Note that the values reported in Tab. IV are normalized with respect to the unregulated system solution (i.e. the objective functions values obtained with Q_{cap}=0, Q_{DG}=0 and m=1).

TABLE IV
OBJECTIVE FUNCTION VALUES OBTAINED FOR A SINGLE LOAD LEVEL

Alternative	F_1 (p.u.)	F_2 (p.u.)	F_3 (p.u.)	F_4 (p.u.)	F_5 (p.u.)
A_1	0.8461	0.7806	0.6856	0.8837	1.0354
A_2	0.8465	0.7727	0.7103	0.9028	1.0343
A_3	0.8867	0.8427	0.0524	0.2929	0.9985
A_4	0.9043	0.8496	0.0623	0.2569	0.8526
A_5	0.8676	0.7899	0.5765	0.7902	0.8335
A_6	0.9011	0.8373	0.0541	0.2774	0.8517

From the analysis of the results reported in Tabs. III and IV and from other results not reported here, it clearly appears that the proposed method is capable of furnishing good alternatives. For example, it furnishes the alternative A_1 which is characterized by the minimum value of the F_1, i.e. the minimum regulation costs, or the alternative A_5 which is characterized by the minimum value of the F_5, i.e. the mean value of THDs, that furnishes the better solution in terms of PQ performances of the test system.

V. CONCLUSIONS

In this paper single-objective and multi-objective optimization problems are formulated and solved in order to achieve the optimal reactive power control of a multi-converter distribution system in presence of DGs and capacitor banks.

In particular, the optimization models are formulated taking into account the impact of the waveform distortions by introducing proper equality and inequality constraints. With such a formulation, it is possible to join the problems related to the management efficiency and those related to the Power Quality problems.

Numerical applications performed on a test distribution system have demonstrated the effectiveness of the proposal and the usefulness of taking into account the Power Quality constraints.

VI. APPENDIX

In Tab. V the rated load powers are reported.

TABLE V
RATED LOAD POWERS

bus	P (kW)	Q (KVAr)	bus	P (kW)	Q (KVAr)
5	28.3	17.6	**60**	28.3	17.6
6	82.8	25.5	**62**	28.3	17.6
9	137.8	44.4	**63**	126.2	41.5
10	68.3	36.9	**65**	28.3	17.6
13	44.4	14.4	**66**	28.3	17.6
14	100.0	48.3	**67**	316.0	120.4
17	79.2	28.4	**70**	79.2	28.4
19	28.3	17.6	**72**	93.4	37.2
21	28.3	17.6	**74**	28.3	17.6
22	28.3	17.6	**75**	28.3	17.6
24	106.7	35.0	**78**	28.3	17.6
26	28.3	17.6	**79**	28.3	17.6
28	28.3	17.6	**81**	28.3	17.6
30	70.8	43.9	**82**	28.3	17.6
33	28.3	17.6	**85**	28.3	17.6
34	28.3	17.6	**86**	56.7	35.1
35	28.3	17.6	**91**	28.3	17.6
39	28.3	17.6	**92**	28.3	17.6
40	14.2	8.8	**93**	28.3	17.6
41	28.3	17.6	**94**	66.6	30.1
43	390.0	135.6	**95**	79.2	28.4
44	28.3	17.6	**96**	360.0	126.2
45	28.3	17.6	**97**	14.2	8.8
46	28.3	17.6	**98**	79.2	28.4
47	28.3	17.6	**100**	28.3	17.6
49	28.3	17.6	**101**	28.3	17.6
51	404.0	194.0	**103**	56.7	35.1
52	28.3	17.6	**104**	28.3	17.6
54	28.3	17.6	**105**	28.3	17.6
55	28.3	17.6	**107**	28.3	17.6
56	28.3	17.6	**108**	28.3	17.6
58	28.3	17.6	**109**	28.3	17.6
59	28.3	17.6			

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