Optimal Dispatching of Distributed Generators and Storage Systems for MV Islanded Microgrids

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Abstract—**This paper presents an optimization procedure that enables the optimal dispatching of distributed generators and storage systems in a medium-voltage islanded microgrid. The network is assumed to be supplied by programmable (dispatchable) and nonprogrammable generators (i.e. nondispatchable, such as renewable energy sources—based units). The optimization goal is to minimize the overall microgrid operating cost and the pollutants emission of the programmable generators, assuming that all of the power made available by the renewable generators (photovoltaic and wind systems) is either directly injected into the network or stored in order to be subsequently delivered according to the proposed storage units' management strategy. The optimization is carried out by a niching evolutionary algorithm (NEA) that is able to find multiple optima and the variation of the objective function in their neighborhood. NEAs allow overcoming the performance of standard algorithms used for optimal power-flow calculations in power systems by avoiding falling into local optima. The optimization procedure is performed on a test microgrid and verified by computer simulations. The numerical results show that the solutions can always improve the microgrid performances irrespective of the network operating conditions in all of the considered cases.**

Index Terms—**Dispatching, dispersed storage and generation, optimal control, power distribution.**

I. INTRODUCTION

DURING the last few years, the number of distributed resources (DRs) has grown significantly and it is expected to get higher in the forseeable future according to the concept of distributed generation (DG), as well as distributed storage (DS). This trend has brought about the need for new electrical distribution paradigms in the framework of "Active networks" [1] and "SmartGrids" [2]. One of the most promising concepts is the microgrid [3], [4], which can be defined such as a cluster of DRs and loads, supplied by a distribution system. The microgrid is able to operate alternatively in grid-connected (or nonautonomous) mode and in islanded (or autonomous) mode.

These various modes of operation require different control methods for microgrid generators. During nonautonomous operation, it is possible to dispatch DG active and reactive powers essentially according to economic criteria, as voltage and frequency control are performed at the level of the main system which the microgrid is connected to. On the other hand, during autonomous operation, it is necessary to control local generators in order to ensure voltage and frequency stability. Primary and secondary droop control has been proposed to emulate the physical behavior of generating and control systems connected to the grid that makes the system stable, as explained in Section III-A [5].

Both primary and secondary droop controls can be implemented in a microgrid on the ground of local measurements, thus reducing the need for communication between generators and a central controller in order to speed up the system response to perturbations while keeping voltage and frequency within the allowed ranges [6]. However, in order to obtain good operation also from the economical viewpoint, a higher level coordinated control action, performed by a hierarchical control system, is required to optimally dispatch the generators after primary and secondary droop controls have taken place.

In this paper, a hierarchical control based on two levels is considered as follows.

- The low-level control is decentralized and is performed by the local controllers of the programmable generators (primary and secondary droop control of voltage and frequency).
- The high-level control has to centrally perform an economic optimization of the operation of the microgrid as a whole, minimizing, at the same time, the pollutants emissions. This is obtained by implementing innovative optimal power flow as well as appropriate storage system management.

The proposed hierarchical control is likely to show the greatest benefits in a scenario where the distribution system operator (DNO) owns and manages programmable generators and storage systems (a condition which is not presently allowed in many countries, for example, in Italy, but considered as a possible development of regulations required by smart-grids implementation).

The optimization procedure is to be performed by a central control unit (CCU), which is part of a microgrid central controller (MGCC) to dispatch the distributed generators that supply the microgrid. The network is assumed to be supplied by programmable and nonprogrammable generators, such as renewable energy sources (RES)—based units, such as photovoltaic and wind systems. More in detail, the optimization goal is to minimize the overall microgrid operating cost and the pollutants emission of the programmable generators, assuming that all of the power made available by the renewable gener-

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Manuscript received May 05, 2011; revised November 02, 2011 and February 03, 2012; accepted April 01, 2012. Date of publication May 21, 2012; date of current version June 20, 2012. Paper no. TPWRD-00371-2011.

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Digital Object Identifier 10.1109/TPWRD.2012.2194514

ators such as photovoltaic and wind systems is either directly injected into the network or stored in order to be subsequently delivered according to the proposed storage units' management strategy. Measured microgrid loads and powers generated by the nonprogrammable generation units are inputs provided to the microgrid CCU. This calculates, by means of the proposed algorithm, the optimal power outputs of programmable generators and storage systems according to the aforementioned goals.

There are different approaches to tackle this kind of optimization problem, such as finding multiple pareto-optimal solutions [7] or optimizing a single multiobjective function obtained by a weighted sum of the targets [8]. The most used optimal power flow (OPF) solution techniques are the Lagrange–Newton method [9] and sequential quadratic programming (SQP) [10].

In the last few years, stochastic optimization methods have been applied to the OPF problem. Reference [11] presents an approach to solve a single objective OPF problem (to minimize the total operating cost in a power system) by means of particle swarm optimization algorithm. In [12], the multiobjective economic-emission OPF problem is solved using a differential evolution algorithm.

This paper presents a well-suited procedure to obtain a weighted-sum objective function and the multiobjective OPF problem is solved by means of a niching evolutionary algorithm (NEA) [13], called the self-adaptive low-high evaluations–evolutionary algorithm (SALHE-EA) [14], because it is able to correctly identify the optimum.

II. GENERALITIES ON ISLANDED MICROGRIDS CONTROL

Appropriate control systems for microgrid local generators are required in order to enable correct management during microgrids temporary or normally autonomous operation. Generally, the control schemes are designed to allow each type of generator to operate in both grid-connected (nonautonomous) and islanded (autonomous) microgrids. In particular, a grid-connected operating mode allows a PQ control on generators, since it is possible to dispatch active and reactive power without local voltage and frequency control, which is ensured by the main grid. On the other hand, when the microgrid is disconnected from the rest of the network, it is necessary to switch to a different generator control mode (i.e., a Vf control), which has to ensure voltage and frequency stability to the islanded network [15].

Starting from the analysis of some works proposed by researchers involved in studying suitable control strategies for autonomous microgrids, a general classification can be proposed taking into account centralized [16]–[18]; distributed [6], [19]–[23]; and hierarchical [24]–[28] architectures.

III. CONTROL STRATEGY

This paper proposes a hierarchical control based on two control levels as follows.

1) The low-level control is decentralized and is performed by the local controllers of the programmable DG units. Typically, the local controllers have to perform a primary and secondary droop control of voltage and frequency.

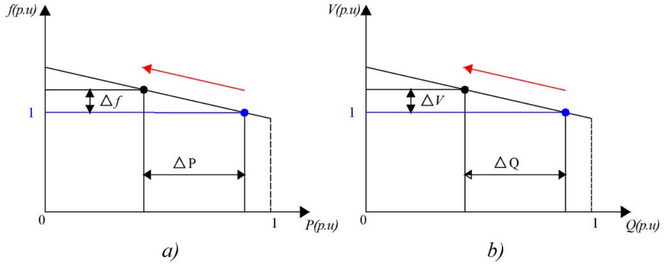

Fig. 1. F-P and V-Q droop characteristics. Effect of primary droop control (low-level control).

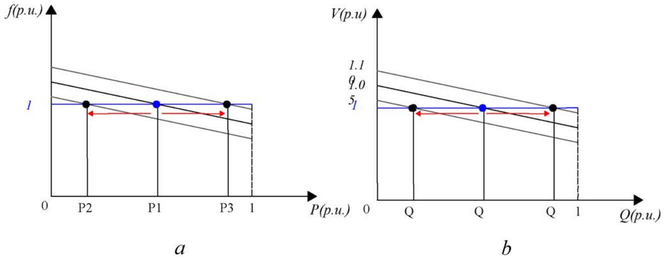

Fig. 2. F-P and V-Q droop characteristics. Effect of secondary droop control (low-level control).

2) The high-level control has to centrally perform an economic optimization of the operation of the microgrid as a whole, minimizing, at the same time, the pollutants emissions. As introduced before, the optimization problem is solved by the CCU, which has to establish a bidirectional communication with the local generators.

A. Low-Level Control

The generation units are equipped with local controllers that are able to adjust the active and reactive power outputs according to droop characteristics as the ones reported in Figs. 1 and 2. Specifically, primary regulation moves the set points along the characteristics, according to the changes in load conditions, causing steady-state frequency and voltage errors (respectively, shown in Fig. 1(a) and (b))

$$\Delta f = k_p \Delta P \tag{1}$$

$$\Delta V = k_q \Delta Q \tag{2}$$

where k_p and k_q represent the negative slopes.

In order to maintain adequate power-quality levels, in terms of keeping voltage and frequency at nominal values, a secondary control is required on the generators output.

This control action can be obtained by translating the droop characteristics, as shown in Fig. 2(a) and (b).

For given different values of P and Q, frequency and voltage can be kept at the nominal values by varying no-load frequency and voltage while keeping the slopes constant.

The droop characteristics will affect the system operation very similarly to what they do in a transmission system supplied by several power generation plants on which primary and secondary control are performed. The slope of the characteristics will determine how the programmable generators share powers among them (primary control), and the variable "height" will determine the possibility of bringing voltage and frequency back to their nominal values (secondary control).

The low-level control can operate to ensure network stability without any support from the high-level control.

This means that any malfunction in the CCU or in the communication infrastructure does not involve misoperation of the local controllers. The contingency would only imply temporary lack of optimization in the microgrid operation. Then, after local frequency and voltage control actions have taken place in order to maintain stable microgrid operation, a further change in the generators' setpoints is possible in order to find the optimal power output which reduces generation costs and pollutants emissions, as explained in the following section.

B. *High-Level Control*

The MGCC acquires the measures of the powers absorbed by loads and generated by the RES. Then, the CCU finds the optimal setpoints of programmable generators and storage systems according to the load conditions.

Subsequently, the MGCC sends the optimal setpoints to the local controllers in order to obtain the desired power output. In practice, the setpoints are implemented by adjusting (i.e., translating) the droop characteristics in order to obtain the required power outputs while maintaining the nominal voltage and frequency levels (power-quality constraints). Different from the secondary control performed at the low level, this one is a centralized and coordinated characteristics adjustment.

The centralized procedure is based on the presence of a database and a monitoring system.

The database contains the following information:

- geometric, topological, and electrical characteristics of the microgrid (i.e. network nominal voltage, incidence matrix [29], branches impedances, lines current carrying capacity);
- capability curves of the programmable generators;
- storage systems capacity;
- generation costs, which include fuels costs and operating and maintaining costs (OMC), as a function of the active power output;
- pollutants emissions as a function of the active power output;
- weighting factors that quantify the relevance given to each objective function.

The monitoring system acquires and sends the following information to the MGCC:

- powers absorbed by loads;
- powers generated by nonprogrammable generators;
- state-of-charge (SOC) storage systems.

To summarize, thanks to the hierarchical control, the power output of programmable generators and storage systems can be set optimally by means of the high-level control that operates at regular time intervals; between two subsequent optimizations, the low-level control can act each time the changed operating conditions call for it, in order to meet power-quality requirements.

IV. OPTIMIZATION PROCEDURE

A. *Optimization Method*

Real-world optimization problems often exhibit multiple optima. Multiple optima (the local optima and the global one) are present when an objective function of multiobjective optimization problems, obtained by the weighted sum of the targets, is multimodal. In this case, it is useful to obtain information about the global optimum and the local ones along with the variation of the objective function in their neighborhood. Actually, if the objective function varies rapidly in the neighborhood of the global optimum, which is chosen as the solution of the optimization problem, the performance achieved by implementing this solution can be worse than the computed one due to unavoidable parameters tolerances. In this case, the best choice is a different optimum (i.e., a local one) in whose neighborhood the objective function varies slowly.

As previously introduced, in this paper, the multiobjective OPF problem requires optimally dispatching distributed generators and storage systems in an MV islanded microgrid. The network is assumed to be supplied by programmable and nonprogrammable generators (such as renewable energy sources-based units). The storage systems are treated as power sources because it is assumed to be known how much power they are able to deliver at the moment of the optimization until the next one is performed.

The weighted sum approach is the most suitable to tackle the proposed multiobjective OPF problem since the information about the relevance of each target is put (*a priori*) in its weight used to obtain the objective function.

Obviously, as highlighted before, the most appropriate solution from the practical implementation viewpoint can be different from the global optimum and can be chosen if the adopted optimization algorithm provides also some information about the local optima and the variation of the objective function in their neighborhood. For these reasons, the optimization problem formulation, described in the following subsection, is tackled by using the weighted sum approach.

There are different techniques for solving the optimization problem. As introduced before, the most commonly used ones are the deterministic ones, but their main drawback is convergence to local optima. Hence, they are not appropriate for solving multimodal problems [30]. The stochastic optimization methods are also affected by such a drawback but, in the last few decades, diversity preservation techniques, such as niching, have been introduced in these algorithms to overcome this limitation [8].

In this paper, the multiobjective OPF problem is solved by means of the SALHE-EA (The Appendix reports the pseudocode of the algorithm), because it is able to correctly identify the global optimum as well as different local optima. Moreover, it provides the niche radius of each optimum overcoming the performance of the aforementioned OPF methods. The niche radius can be considered as a measure of the variation of the objective function in the neighborhood of the optimum: a low niche radius means that the objective function decreases rapidly within the niche. The global optimum provided by SALHE-EA is chosen as the CCU output.

B. Problem Formulation

The goal of the optimization is to realize optimal dispatching of distributed generators in an MV autonomous microgrid to minimize its operating costs and emissions.

In addition, in order to reach this objective, when all of the power made available by the RES is less than the whole network load, it is injected into the microgrid and an optimal management of the power output of the storage systems is adopted. On the other hand, when the available RES power is greater than the load, this can be supplied by the RES only while the exceeding power can be stored. Besides this, it could be impossible to inject all of the RES available power into the network due to the need to ensure power balance through the low-level control of the generators.

The goals of the storage systems' management strategy are to inject into the microgrid the power amount that allows the programmable generators to work at their best operating point as well as to avoid starting up the programmable generators that are turned off, if possible. Moreover, the storage systems' management strategy must be capable of reaching the aforementioned goals by minimizing the usage of the energy stored.

The procedure is accomplished by solving a nonlinear-constrained multiobjective optimization problem whose solutions are the optimal power outputs required from the programmable generators and the storage systems.

In order to normalize the aforementioned three objectives, their maximum values have been calculated, as indicated in the following text.

The operating cost objective function is

$$f_1 = 1 - \frac{T \sum_{k=1}^{\mathrm{NDG}} C_k(P_k) \cdot P_k + \sum_{k=1}^{\mathrm{NDG}} C_{\mathrm{ON,k}} \left[1 - I_k^{t-T}\right] I_k^t}{C_{\max}} \tag{3}$$

where

NDG	number of programmable DG units;
T	time interval (in hours) between two subsequent optimizations;
P_k	active power (in kilowatts) generated by the kth programmable DG unit;
$C_k(P_k)$	cost (Euros per kilowatt-hour) of the active power of the kth programmable DG unit as a function of the active power output;
$C_{ON,k}$	startup cost of the kth programmable generator;
$C_{\max}$	maximum operating cost (Euros) obtained when all programmable generators are switched on and they produce their maximum power;
I_k^{t-T}	status $(1 = \mathrm{ON}, 0 = \mathrm{OFF})$ of the kth programmable generator at time $t - T$ (at which the previous optimization has been performed);
I_k^t	status $(1 = \mathrm{ON}, 0 = \mathrm{OFF})$ of the kth programmable generator at time t (at which the optimization is performed).

Hence, f_1 can be maximized to minimize the operating cost. The pollutants emissions objective function is

$$f_2 = 1 - \frac{T \sum_{k=1}^{\mathrm{NDG}} E_k(P_k)}{E_{\max}} \tag{4}$$

where

$E_k(P_k)$	pollutants emission (tons per hour) from the kth programmable DG unit as a function of the active power output;
$E_{\max}$	maximum pollutants emission (tons) obtained when all programmable generators produce their maximum power.

In addition, the storage systems-management objective function is

$$f_3 = 1 - \frac{\sum_{k=1}^{NS} P_k}{P_{\max}} \tag{5}$$

where

P_k	active power (in kilowatts) generated by the kth storage system;
P_{max}	sum of the maximum active power output of all storage systems.

Hence, f_3 can be maximized to minimize the usage of the energy stored in the storage system.

The three normalized objective functions described before are then combined in a single function to be maximized

$$f = \lambda_1 f_1 + \lambda_2 f_2 + \lambda_3 f_3 \tag{6}$$

where λ_1, λ_2, and λ_3 are the weighting factors that quantify the relevance given to each objective by the MGO (the sum of the weighting factors is 1).

The optimization problem is subject to constraints as follows.

- The capability curves establish synchronous generators active and reactive power limits (Fig. 3).
- Balance between the load, generation, and power losses must be ensured.
- Standard EN 50160 establishes the upper and lower limits on the node voltage variations $(1.1 \cdot V_{\mathrm{nom}}$ and $0.9 \cdot V_{\mathrm{nom}})$.
- The lines thermal limits establish the conductors current-carrying capacity.

V. TEST MICROGRID

Fig. 4 shows the 20-kV microgrid used to test the proposed optimization procedure. The characteristics of the cable lines (conductor section 3 × 95 mm^2) are given in Table I, which shows the data related to length, resistance, and reactance for each branch $(\mathrm{B1}, \ldots, \mathrm{B37})$.

Table II shows the position and nominal apparent power of the loads $(\mathrm{L1}, \ldots, \mathrm{L26})$.

Table III shows the position and nominal apparent power of the RES, which are nonprogrammable generators (NPGs).

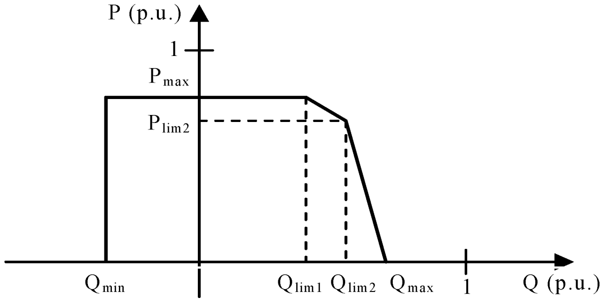

Fig. 3. Schematic representation of the synchronous capability.

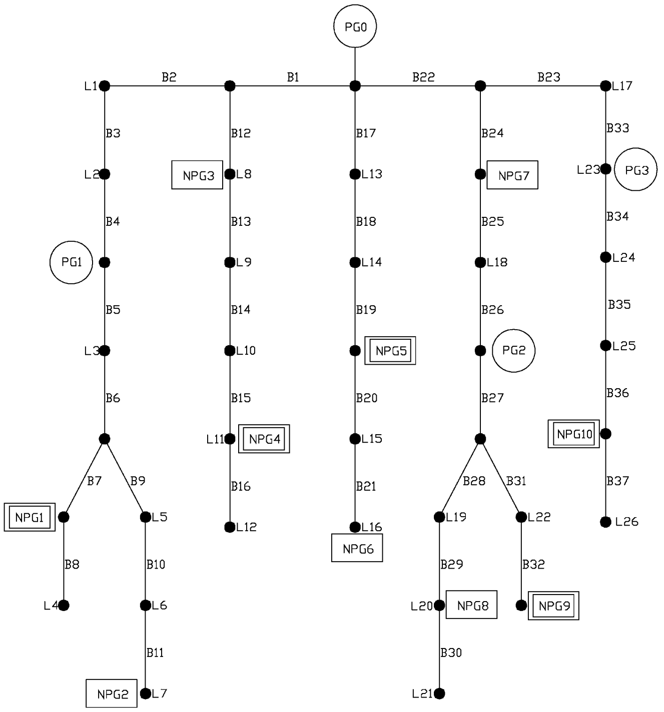

Fig. 4. Test microgrid. (NPGs associated with a storage system are indicated by a double rectangle.)

TABLE I
MICROGRID BRANCHES DATA

Branch	Length (km)	R (Ω)	X (Ω)	Branch	Length (km)	R (Ω)	X (Ω)
B1	3	0.579000	0.329867	B20	0.5	0.096500	0.054978
B2	3	0.579000	0.329867	B21	0.5	0.096500	0.054978
B3	1	0.193000	0.109956	B22	3	0.579000	0.329867
B4	1	0.193000	0.109956	B23	2	0.386000	0.219911
B5	1	0.193000	0.109956	B24	1	0.193000	0.109956
B6	1	0.193000	0.109956	B25	1	0.193000	0.109956
B7	1	0.193000	0.109956	B26	0.5	0.096500	0.054978
B8	0.5	0.096500	0.054978	B27	0.5	0.096500	0.054978
B9	0.5	0.096500	0.054978	B28	0.5	0.096500	0.054978
B10	0.5	0.096500	0.054978	B29	0.5	0.096500	0.054978
B11	1.5	0.289500	0.164934	B30	0.5	0.096500	0.054978
B12	1.5	0.289500	0.164934	B31	0.5	0.096500	0.054978
B13	1.5	0.289500	0.164934	B32	0.5	0.096500	0.054978
B14	0.5	0.096500	0.054978	B33	1.5	0.289500	0.164934
B15	0.5	0.096500	0.054978	B34	1	0.193000	0.109956
B16	0.5	0.096500	0.054978	B35	0.5	0.096500	0.054978
B17	1	0.193000	0.109956	B36	0.5	0.096500	0.054978
B18	1	0.193000	0.109956	B37	0.5	0.096500	0.054978
B19	0.5	0.096500	0.054978				

TABLE II
MICROGRID LOADS DATA

Load	Node	S (kVA)	cosφ	Load	Node	S (kVA)	cosφ
L1	2	800.000	0.9	L14	18	800.000	0.9
L2	3	800.000	0.9	L15	20	400.000	0.9
L3	5	800.000	0.9	L16	21	400.000	0.9
L4	8	800.000	0.9	L17	23	800.000	0.9
L5	9	600.000	0.9	L18	25	600.000	0.9
L6	10	600.000	0.9	L19	28	800.000	0.9
L7	11	800.000	0.9	L20	29	400.000	0.9
L8	12	600.000	0.9	L21	30	400.000	0.9
L9	13	600.000	0.9	L22	31	800.000	0.9
L10	14	800.000	0.9	L23	33	600.000	0.9
L11	15	800.000	0.9	L24	34	600.000	0.9
L12	16	800.000	0.9	L25	35	800.000	0.9
L13	17	600.000	0.9	L26	37	800.000	0.9

TABLE III
MICROGRID NONPROGRAMMABLE GENERATORS DATA

Gen.	Node	S (kVA)	cosφ	Gen.	Node	S (kVA)	cosφ
NPG1	7	600.000	1	NPG6	21	400.000	1
NPG2	11	400.000	1	NPG7	24	400.000	1
NPG3	12	400.000	1	NPG8	29	400.000	1
NPG4	15	600.000	1	NPG9	32	600.000	1
NPG5	19	600.000	1	NPG10	36	600.000	1

TABLE IV
MICROGRID STORAGE SYSTEMS DATA

Storage	Node	P (kW)
S1	7	600.0
S2	15	600.0
S3	19	600.0
S4	32	600.0
S5	36	600.0

TABLE V
POWER-LIMIT VALUES FROM THE CAPABILITY CURVES AND STARTUP COSTS OF THE PROGRAMMABLE GENERATORS

Gen.	Node	S kVA	P_{max} kW	P_{lim2} kW	Q_{min} kVAr	Q_{lim1} kVAr	Q_{lim2} kVAr	Q_{max} kVAr	€
PG0	0	6250	5000	4500	-2000	2500	3250	4250	26.62
PG1	4	5000	4000	3600	-1600	2000	2600	3400	23.00
PG2	26	3750	3000	2700	-1200	1500	1950	2550	20.23
PG3	33	4375	3500	3150	-1400	1750	2275	2975	22.43

In Table IV, storage systems position and maximum active power are reported.

Table V shows position, nominal apparent power, and power limits (referred to the capability curves shown in Fig. 3) and the startup costs (Euros) of the programmable DG units (called PGs). It is worth noting that the programmable generators' capacity is adequate to supply the entire load, if necessary.

Table VI shows the hourly cost of the PGs active power as a function of the PGs power outputs (Euros per kilowatt-hour).

Table VII shows the hourly pollutants emissions (tons per hour) from the PGs as a function of the power outputs.

The information provided by Tables VI and VII has been used to obtain costs and emissions as functions of the variable "power output" by linear interpolation.

TABLE VI
HOURLY COST OF PGS ACTIVE POWER (EUROS/kWh)

Load Gen.	25%	50%	75%	85%	100%
PG0	0.212983	0.197222	0.173578	0.182611	0.190897
PG1	0.230023	0.228866	0.207815	0.205895	0.210156
PG2	0.269726	0.252007	0.227461	0.239612	0.244268
PG3	0.256398	0.239991	0.220034	0.223677	0.234987

TABLE VII
HOURLY POLLUTANTS EMISSION FROM PGS (TON/h)

Load Gen.	25%	50%	75%	85%	100%
PG0	9.78	15.49	21.78	24.55	29.99
PG1	7.57	12.17	17.00	18.55	23.23
PG2	5.01	8.11	11.22	12.99	15.96
PG3	6.12	10.11	13.67	15.83	19.90

TABLE VIII
SCENARIOS

Scenario	Load Demand %	NPGs Output %	Programmable Generators Status			
			PG0	PG1	PG2	PG3
1	100	100	ON	ON	OFF	ON
2	100	100	ON	OFF	OFF	ON
3	100	100	ON	OFF	ON	ON
4	100	50	ON	ON	OFF	ON
5	100	50	ON	OFF	OFF	ON
6	100	50	ON	OFF	ON	ON
7	70	50	ON	ON	OFF	ON
8	70	50	ON	OFF	OFF	ON
9	70	50	ON	OFF	ON	ON

TABLE IX
WEIGHTING FACTORS COMBINATIONS

λ_1	λ_2	λ_3
0.475	0.475	0.05
0.633	0.317	0.05
0.317	0.633	0.05
0.45	0.45	0.1
0.6	0.3	0.1
0.3	0.6	0.1
0.425	0.425	0.15
0.567	0.283	0.15
0.283	0.567	0.15

VI. OPTIMIZATION RESULTS

This section presents the results of the proposed optimization procedure performed under various operating conditions. The analyzed scenarios are shown in Table VIII.

The optimization is performed for nine different combinations of values of the weighting factors λ_1, λ_2, and λ_3, reported in Table IX, in order to investigate the influence on the results due to relevance assigned to the different objectives.

In the following text, the optimal feasible solution found by means of the SALHE-EA is called *Optimum*, while a feasible, but nonoptimal, solution, which, in practice, could be obtained by the microgrid low-level control (without any optimization), is called*NOS*.

These analyses want to highlight the average advantage that can be achieved thanks to the optimization procedure with respect to the microgrid low-level control in terms of costs and pollutants emissions. To do this, the costs and emissions percentage difference between the optimum and a NOS has been computed as

$$\Delta C = \frac{100 \sum_{i=1}^{nt} \frac{C_{\mathrm{NOS,i}} - C_{\mathrm{OPT,i}}}{C_{\mathrm{OPT,i}}}}{nt} \tag{7}$$

$$\Delta E = \frac{100 \sum_{i=1}^{nt} \frac{E_{\mathrm{NOS,i}} - E_{\mathrm{OPT,i}}}{E_{\mathrm{OPT,i}}}}{nt} \tag{8}$$

where

n_t	number of trials;
C_{NOS}	cost (Euros) for the NOS;
C_{OPT}	cost (Euros) for the optimum;
E_{NOS}	pollutants emission (tons) for the NOS;
E_{OPT}	pollutants emission (tons) for the optimum.

Note that positive values of ΔC and ΔE mean an improvement in costs and emissions, respectively.

Specifically, the results are worked out by choosing as NOS the feasible solution with the lowest fitness among all of those evaluated by the SALHE-EA during the optimization procedure. Parameter T used in (3) and (4) is set to 20 min. The SALHE-EA parameters (e.g., population size, mutation probability, etc.) are set as reported in [31]. The number of objective function evaluations in the stochastic section of SALHE-EA is set to 5000.

Table X shows the results averaged on 10 trials for each scenario.

The numerical results highlight the ability of the optimization procedure implemented by the high-level control to reduce the operating costs and the pollutants emissions always, with respect to the operating conditions obtained by the low-level control.

Moreover, in the various considered scenarios, we obtain different improvements in costs and emissions. This highlights that the effectiveness, and the advantage of the optimization depend on the microgrid operating conditions when the optimization is performed. Also, note that it is very often possible to cut costs and emissions by half (e.g., in Scenarios 7–9 with [$\lambda_1 = 0.475$; $\lambda_2 = 0.475$; $\lambda_3 = 0.05$], [$\lambda_1 = 0.633$; $\lambda_2 = 0.317$; $\lambda_3 = 0.05$] and [$\lambda_1 = 0.317$; $\lambda_2 = 0.633$; $\lambda_3 = 0.05$]).

Finally, the results show that the greater the load to supply by means of the PGs and the storage systems, the lower the ability of the optimum to outperform the NOS.

Table XI, reports the results obtained in Scenario 1 for a single trial using $\lambda_1 = 0.567$, $\lambda_2 = 0.283$, and $\lambda_3 = 0.15$. Note that in the first column P_{PGi} and Q_{PGi} are, respectively, the active and reactive powers from the ith programmable generator.

The results show the ability of SALHE-EA to provide a solution better than the NOS in terms of costs and pollutants emissions. Moreover, it can be seen that SALHE-EA is able to achieve the goal of the storage systems management strategy adopted (keeping programmable generators at their

TABLE X
COSTS AND POLLUTANTS EMISSIONS PERCENTAGE DIFFERENCE BETWEEN THE OPTIMUM AND AN NOS IN THE VARIOUS SCENARIOS

Scenario	**0.475 - 0.475 - 0.05**		**0.633 - 0.317 - 0.05**		**0.317 - 0.633 - 0.05**	
	ΔC	ΔE	ΔC	ΔE	ΔC	ΔE
1	40.68%	26.91%	42.02%	26.45%	35.40%	30.77%
2	37.83%	25.67%	40.10%	27.14%	34.65%	32.43%
3	37.67%	28.06%	39.69%	30.02%	30.25%	32.21%
4	25.73%	23.89%	26.90%	24.76%	23.73%	28.01%
5	25.92%	25.50%	27.34%	25.81%	23.55%	26.96%
6	26.49%	24.90%	26.76%	25.28%	24.27%	28.41%
7	61.25%	39.59%	61.72%	38.98%	49.94%	43.47%
8	65.43%	43.13%	66.26%	39.37%	53.79%	45.65%
9	61.75%	45.00%	59.85%	38.53%	49.42%	44.88%
	0.45 - 0.45 - 0.1		**0.6 - 0.3 - 0.1**		**0.3 - 0.6 - 0.1**	
	ΔC	ΔE	ΔC	ΔE	ΔC	ΔE
1	34.70%	21.57%	35.23%	20.29%	38.15%	27.07%
2	38.41%	25.15%	34.78%	20.92%	33.69%	26.59%
3	32.11%	23.91%	34.31%	22.53%	30.97%	28.57%
4	24.94%	22.92%	25.90%	24.95%	21.68%	26.33%
5	23.83%	24.06%	22.98%	21.03%	21.32%	26.80%
6	24.82%	23.12%	26.09%	22.87%	23.51%	25.16%
7	61.03%	37.67%	54.50%	32.37%	53.77%	40.13%
8	56.09%	37.32%	56.04%	34.20%	49.35%	36.23%
9	57.08%	35.63%	50.06%	32.83%	49.77%	39.56%
	0.425 - 0.425 - 0.15		**0.567 - 0.283 - 0.15**		**0.283 - 0.567 - 0.15**	
	ΔC	ΔE	ΔC	ΔE	ΔC	ΔE
1	21.21%	8.46%	17.93%	5.79%	11.28%	3.22%
2	16.09%	5.11%	15.08%	5.44%	12.72%	4.25%
3	9.73%	2.16%	17.65%	8.12%	7.92%	2.96%
4	8.33%	6.98%	8.12%	4.92%	9.50%	9.97%
5	9.55%	8.93%	9.70%	6.97%	7.78%	7.89%
6	10.72%	9.39%	10.39%	8.59%	9.18%	8.90%
7	24.86%	8.49%	24.08%	6.98%	8.59%	4.43%
8	11.96%	5.29%	23.84%	10.57%	6.42%	2.22%
9	16.77%	7.71%	24.93%	13.77%	7.06%	2.39%

TABLE XI
GENERATORS' DISPATCHING, COSTS, AND EMISSIONS FOR THE OPTIMAL SOLUTION AND THE NOS IN SCENARIO 1

	Optimum	NOS
P_{PG0} (kW)	3749.9	1254.6
Q_{PG0} (kVAr)	2871.6	3747.7
P_{PG1} (kW)	3022.1	3658.6
Q_{PG1} (kVAr)	3460.1	2876.8
P_{PG2} (kW)	0.0	2930.1
Q_{PG2} (kVAr)	0.0	1600.6
P_{PG3} (kW)	2623.6	1707.7
Q_{PG3} (kVAr)	2797.5	2039.9
P_{S1} (kW)	280.1	369.7
P_{S2} (kW)	198.3	78.4
P_{S3} (kW)	371.6	204.8
P_{S4} (kW)	341.1	103.7
P_{S5} (kW)	292.1	572.2
Costs (€)	464.00	558.22
Emissions (ton)	13.13	13.95
Fitness	0.444779	0.389284
Niche radius	0.17	-

best operating point and avoiding starting up the programmable generators that are turned off, while minimizing the use of the stored energy). In fact, the PGs power output related to the optimum is close to their best operating point (in this case, 75% of $P_{\max}$ as shown in Table VI). Further, the optimum avoids starting up the PGs that were turned-off (PG2 in this example).

Note that the optimum reaches this goal by asking to the storage systems about the same overall power required by the NOS. On the other hand, the PGs power output related to the NOS is far from the generators best operating points. In detail, the power output of PG0, PG1, PG2, and PG3 is the 25.10%, 91.45%, 97.67%, and 48.80% of each $P_{\max}$, respectively. An additional disadvantage of the NOS with respect to the optimum is starting up PG2.

VII. CONCLUSION

In this paper, the problem of optimal dispatching of local resources in MV temporary or permanently islanded microgrids supplied by programmable and nonprogrammable generators (based on RES) and storage systems has been dealt with. The optimization goal was to minimize the overall microgrid operating cost and the pollutants emission of the programmable generators, assuming that all of the power made available by the renewable generators was either directly injected into the network or stored in order to be subsequently delivered according to a storage units' management strategy. Such a strategy permits injecting into the microgrid the amount of stored power that, on one hand, allows the programmable generators to be kept at their best operating point, and on the other, allows avoiding starting up the turned-off programmable generators, if possible.

The weighted-sum approach has been considered to be the most suitable one to tackle the multiobjective OPF problem, because the information about the relevance of each target is put in its weight, which is used to obtain the objective function. Hence, the global optimum provided by the optimization algorithm can be directly treated as the microgrid CCU output.

The proposed optimization procedure has been performed on a test microgrid and verified by computer simulations. The multiobjective OPF problem has been solved by means of SALHE-EA.

The numerical results highlighted the ability of the optimization procedure to reduce the operating costs and the pollutants emissions by means of an optimal dispatching of distributed generators and storage systems. In particular, it is shown that SALHE-EA has been able to perform an optimal management of the storage systems, which allows the PGs to operate close to their best operating point and to be started up only when it is necessary. Moreover, the numerical results have shown that the solutions provided by the optimization algorithm can always improve the microgrid performances independently from the network operating conditions in all of the considered cases, although the effectiveness and the advantage of the optimization procedure obviously depend on the microgrid operating conditions when the optimization is performed.

A future development of this work can be the coordination between optimal microgrid planning (in terms of the components' location and sizing) with the proposed optimal-management strategy.

APPENDIX A

Pseudocode of SALHE-EA. A detailed description of each step of the algorithm is provided by [14].

```
begin
    generates random population
    do ng times
        evaluation of fitness functions, fH and fL, for each
        individual in the population
        selection
        mutation
        elimination of useless individuals
        identification of new hypothetical maxima and
        new hypothetical minima
        updating of niche radii
    end do
    deletion of doublets
    starting of PS algorithm from each hypothetical
    maxima
    updating of niche radii
    deletion of doublets
end
```

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