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Economic Dispatch for on-line operation of grid-connected microgrids

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Abstract. In this paper, a control strategy for real-time operation of a master-slave controlled microgrid is developed. The basic idea of this control strategy is to schedule all dispatchable energy sources available into a microgrid to minimize its operational costs. Control actions are centrally evaluated by solving a two-stage optimization problem formulated to take place on two different time-scales: in the day-ahead and in the real-time. The first one provides a 24-hour plan in advance. It mainly draws up the active power levels that Distributed Energy Resources (DERs) should provide for each quarter hour of the next day by taking into account energy prices of the day-ahead energy market, the forecasted energy production of non-dispatchable renewables and loads. The real-time optimization problem updates the active power set-points of DERs in order to minimize as much as possible the real-time deviations between the actual power exchanged with the utility grid and its scheduled value. The effectiveness of the proposed methodology has been experimentally tested on an actual microgrid.

Key words: microgrids, on-line economic dispatch, distributed energy sources, active distribution networks, microgrid planning.

1. Introduction

During the last years, intensive economic support programs have been provided by several countries all over the world to finance research projects aimed at promoting the development of microgrids. As a result, different kinds of microgrids have been developed [1–6]. Most of them may operate in a grid-tied mode and bring a lot of benefits to power systems. In spite of this, the tendency to operate multiple energy providers in a microgrid under a deregulated energy market can give rise to conflictual operations between them, which may result in the reduction of safety margins [7]. The need to develop adequate control strategies able of minimizing these issues has therefore grown. The emphasis is often on market-oriented approaches aimed at maximizing the economic operation of the whole system. In these methods, the problem of the optimal coordination among DERs has been formulated as an optimization problem aimed at minimizing the trade-off between its internal production and the power exchanged with the utility grid. The solution of this problem can be obtained in a variety of ways, giving rise to a wide variety of algorithms [8–11]. Most of them suggest treating the utility grid as a One-Machine Infinite-Bus (OMIB) system. This simplification gave rise to control schemes that are capable of managing microgrids as independent entities using the main grid as the necessary support for its security problems [12]. As a consequence, related costs due to the required import or export of power from/to the utility grid can be only monitored and not optimized. To overcome the inherent limitation of these methods, many optimization strategies were suggested, such as the Game Theory [13, 14], the Incentive Based Demand Response Program [15] and the Dynamic Programming [16]. The main drawback of these methods is their limited ability to comply with uncertainties associated with forecasting errors in loads, energy prices and non-dispatchable renewable energy productions.

Energy Storage Systems (ESSs) seems to be a suitable solution to tackle this problem due to their fast response time. As a consequence, several control strategies have been developed for the optimal management of such devices. These strategies differ in their specific assumptions regarding the decision-making strategy on how to dispatch the ESS power. In this sense, it can be found that control strategies such as those referred to in [17] adopt ESSs to provide a peak load shaving. In [18] operating and maintenance costs of ESSs can be directly integrated into the objective function and optimized by Dynamic Economic Dispatch procedures as suggested in [18] or by the Mixed-Integer Non-Linear Programming (MINLP) method as in [19].

Despite numerous research efforts have been devoted to adopting ESS for improving operational performance of a microgrid, their accuracy is still affected by the precision of the adopted forecasting methods.

To overcome this issue, two-stage coordinated control approaches have been suggested in [20–24]. These approaches are based on a two-step optimization problem, one running in the day-ahead market and the other one running in the intraday market to reallocate, in the best economic way, excess or shortcoming power due to forecast errors or unpredicted events. Anyway, since both day-ahead and intra-day schedules consider the microgrid evolving through steady-state equilibrium points, they need short-term forecasts of load and non-

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programmable RES power. As a consequence, their accuracy is still affected by the precision of the adopted forecasting method.

In the attempt to reduce the need of short term forecast and instead rely on actual demand and supply, in this paper an on-line economic dispatch methodology has been developed.

The main aim of this methodology is to adjust in the on-line environment the active power outputs of all programmable resources available into a microgrid so as to minimize as much as possible any possible unbalances occurring on the system due to forecast errors.

To prove the effectiveness of the proposed methodology experimental tests have been performed on an actual microgrid [25].

2. Mathematical formulation of the on-line economic dispatch

The aim of this section is to develop an Energy Management System (EMS) that is able to optimize in the on-line environment the operation of a grid-connected microgrid.

Without loss of generality, let us assume a microgrid containing n_G dispatchable generators (DGs), n_{RES} non-dispatchable RES, n_S energy storage systems (ESSs) and n_L loads.

The main objective of this EMS is to manage in the continuous time domain all available energy sources so as to minimize microgrid operating costs while meeting the actual load demand. To comply with this exigency a two-stage control architecture has been developed as shown in Fig. 1.

Firstly, the EMS determines the optimal power exchange schedule with the utility grid and the optimal schedule for all available DGs according to the prices of electricity in the energy market and forecast data electrical load demand and RES power production. The results of the day-ahead economic dispatch are then used, along with actual renewables availability and load demand, to execute the on-line Economic Dispatch problem. The main aim of this problem is to adjust, in the on-line environment, the n_G dispatchable generator outputs so as to cover the unavoidable power imbalances between scheduled levels of generation and load caused by forecast errors or unforeseen events.

Insights on these stages are given in the following subsections.

2.1. Forecasting module. The aim of this block is to provide the day-ahead economic dispatching module with the necessary input data. To comply with this exigency, it will be assumed in the following that the day-ahead variables needed for the economic dispatch are forecasted using one of the methods available in the literature, such as those adopting similar day approaches [26] or time series models [27–31].

The selection of one forecasting method rather than another depends on specific factors such as the targeted time, the result-

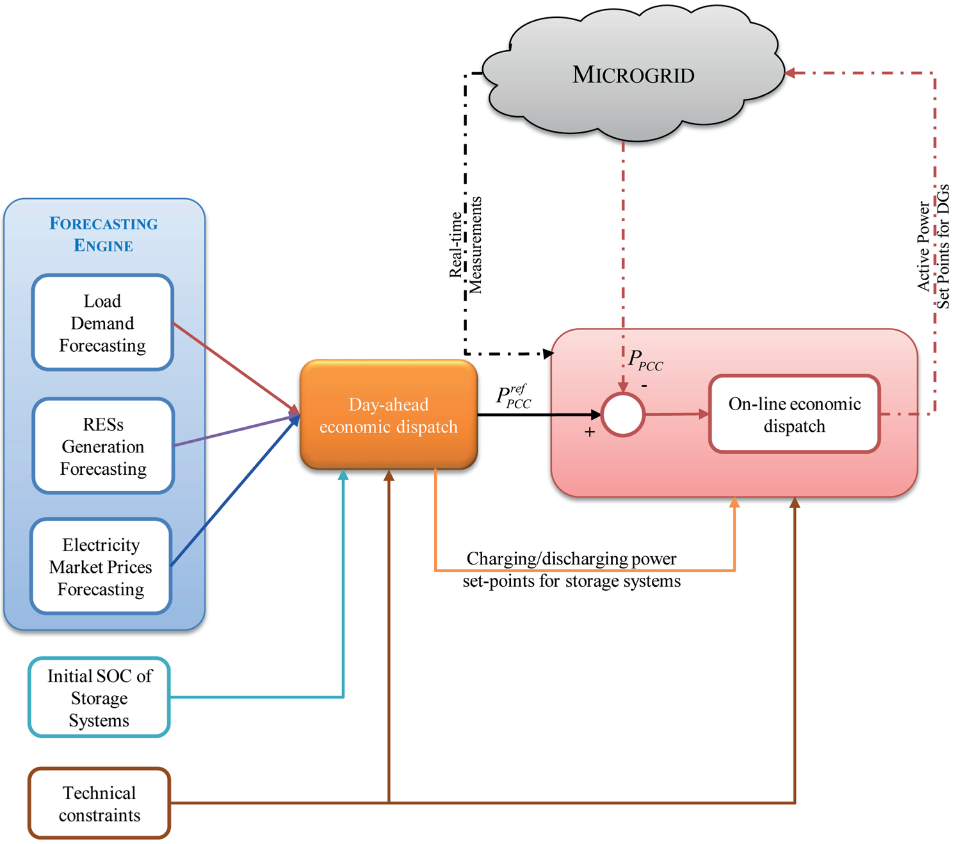

Fig. 1. The on-line economic dispatch schedule

ing accuracy, and the available data and information. Details of this selection process are beyond the scope of this paper.

2.2. Day-ahead economic dispatch block. The aim of this block is to schedule, with 15-min programming time steps, the output power of n_G dispatchable generators, charge/discharge rates of n_S ESSs and the imported/exported power from/to the upstream grid to minimize the microgrid operating costs and the expenses of energy purchased from the utility grid.

To achieve this objective, classic day-ahead economic dispatching methods like the one developed in [32] can be adopted. This method is based on an optimization scheme involving an integral constraint for the State-Of-the-Charge (SOC) of ESSs and thus, it allows preserving the availability of such devices for the whole day.

2.3. On-line economic dispatch block. The aim of this stage is to guarantee the power balance in the microgrid. From a mathematical point of view, this problem can be formalized as an optimization problem aimed at minimizing unavoidable power deviations between scheduled levels of generation and actual load due to forecasting errors by acting on all dispatchable energy resources (DER) available into the microgrid, i.e. DGs and ESSs.

Denoting with $\overline{P}_{DER}$ and P_L^m, the scheduled generation level and the actual load, respectively, the microgrid power unbalance can be defined as follows:

$$\Delta P_L^m = \overline{P}_{DER} - P_L^m \,. \tag{1}$$

The goal of the proposed procedure is to adjust the active power injected by all DER until the power unbalance is either zero or minimal. Moreover, since the overall power required to restore the active power balance within the microgrid is not cost-free, a least-cost dispatch of DER units is implemented in this regulation service. Therefore, the overall optimization problem can be formalized as follows:

$$\min_{P_{DER,i}} J = \min_{P_{DER,i}} \left(\sum_{i=1}^{n_{DER}} C_{DER,i}\left(P_{DER,i}(t)\right) \right) \tag{2}$$

where:

- $P_{DER,i}$ is the active power set-points of the i-th DER unit;
- $C_{DER,i}$ is the cost function of the i-th DER;
- N_{DER} is the total number of DER available into the microgrid $(n_G + n_{ESS})$.

For these microgrids that can be isolated from the main grid, the EMS will also take care of guaranteeing adequate reserve margins. To comply with this exigency, the SOC level of all available ESSs needs to be kept at a desired range. To achieve this objective, ESSs are not involved in the regulation mechanism and their power outputs are kept fixed at day-ahead scheduled values:

$$P_{S,s}^m = \overline{P}_{S,s} \tag{3}$$

where $P_{S,s}^m$ and $\overline{P}_{S,s}$ are the active power actually measured at the terminals of the s-th ESS and its day-ahead scheduled value.

As a consequence, the total power unbalance will be shared only among all available DGs and thus the objective function can be reformulated as:

$$\min_{P_{G,i}} J = \min_{P_{G,i}} \left(\sum_{i=1}^{n_G} C_{G,i}\left(P_{G,i}(t), \alpha_{G,i}, \beta_{G,i}, \gamma_{G,i}\right) \right) \tag{4}$$

where $C_{G,i}$ is the cost function, $\alpha_{G,i}$ [€/kW^{2}h], $\beta_{G,i}$ [€/kWh] and $\gamma_{G,i}$ [€/h] are the cost coefficients of the i-th DG.

While minimizing the objective function stated in (3), the following equality and inequality constraints should be satisfied:

Power balance constraint

$$\begin{aligned} P_{PCC}^m(t) + \sum_{i=1}^{n_G} P_{G,i}^m(t) + \sum_{j=1}^{n_{RES}} P_{RES,j}^m(t) + \sum_{h=1}^{n_S} \overline{P}_{S,s}(t) \\ - \sum_{k=1}^{n_L} P_{L,k}^m(t) = 0 \end{aligned} \tag{5}$$

where:

- P_{PCC}^m is the active power exchange between the microgrid and the utility grid actually measured at the Point of Common Coupling (PCC);
- $P_{G,i}^m$ is the actual active power production of the i-th DG;
- $P_{RES,j}^m$ is the active power actually measured at the terminals of the j-th non-dispatchable RES;
- $P_{L,k}^m$ is the active power actually measured at the terminals of the k-th load.

Generation capacity

$$P_{G,i}^{\min} \le P_{G,i} \le P_{G,i}^{\max} \tag{6}$$

where $P_{G,i}^{\min}$ and $P_{G,i}^{\max}$ is the minimum and the maximum power producible by the i-th DG unit.

2.3.1. On-line optimization algorithm. The problem stated in (3)–(6) is specified for any fixed operating point and thus it can be solved adopting classic solution methods. Anyway, if it wants to develop an on-line controller that is able to reveal all changes occurring on the microgrid operating point, an optimization methodology operating in the continuous time domain needs to be developed.

To comply with this exigency, an optimization algorithm derived from Lagrangian method has been adopted. The solution of the optimization problem can be obtained assuming that all DG units operate at the same incremental cost.

$$\lambda = \frac{\Delta P_L^m + \sum\limits_{i=1}^{n_G} \dfrac{\beta_i}{2\gamma_i}}{\sum\limits_{i=1}^{n_G} \dfrac{1}{2\gamma_i}} \,. \tag{7}$$

Based on Eq. (7), the optimization problem can be algebraically solved using the following function for each dispatchable generator:

$$P_{G,i} = \frac{\lambda - \beta_i}{2\gamma_i} \quad \text{for} \quad i = 1, \ldots, n_G \,. \tag{8}$$

From Eq. (8) it is evident that the evaluated control actions are not constrained and thus some units can be called to provide active power exceeding their allowable limits. To overcome this issue, thresholds defined by upper $P_{G,i}^{\max}$ and lower $P_{G,i}^{\min}$ limits are included into the control loop. Therefore, the active power set points evaluated by Eq. (8) are checked for lower and upper limit violations. If n_{AP} DGs are violating their active power limits, the algorithm will fix the value of their active power to the corresponding limits and the new incremental cost is evaluated:

$$\lambda^{new} = \frac{\Delta P_L^m + \sum_{i=1}^{N} \frac{\beta_i}{2\gamma_i}}{\sum_{i=1}^{N} \frac{1}{2\gamma_i}} \tag{9}$$

where N is the number of the generators that can be committed and it can be evaluated as follows:

$$N = n_G - n_{AP}. \tag{10}$$

Substituting Eq. (9) into Eq. (8) the new active power set-points for N DGs non violating their limits can be derived:

$$P_{G,i}^{new} = \frac{\lambda^{new} - \beta_i}{2\gamma_i} \quad \text{for} \quad i = 1, \ldots, N. \tag{11}$$

In doing this, the proposed controller is able to share automatically the control burden among the remaining DG units, moving the system in a suboptimal condition.

3. Implementation of the proposed economic dispatch algorithm

The two-stage economic dispatch algorithm developed in the previous section can be implemented on the basis of the flow chart shown in Fig. 2.

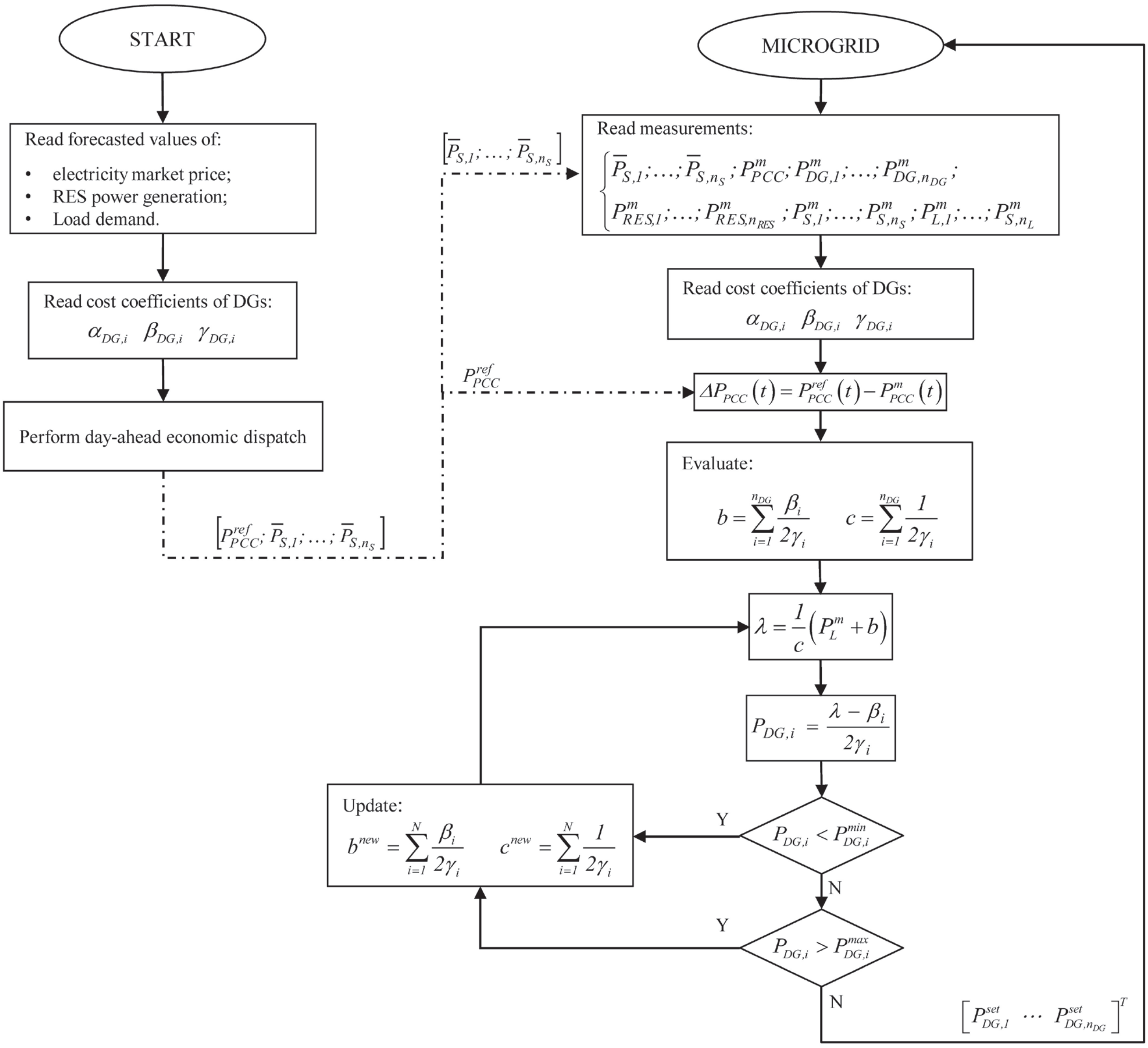

Fig. 2. Flow-chart of the proposed economic dispatch scheduler

As can be noted, the proposed methodology is based on the following steps:

Stage 1. Day-Ahead Economic Dispatch
1. Read the day-ahead forecasted values of electricity market price as well as of RES power production and loads;
2. Read the initial SOC of ESS;
3. Evaluate the 24-hour plan of power outputs of all dispatchable generators, charge/discharge rates of ESSs and the grid exchange power profile.

Stage 2. On-line Economic dispatch
1. Set the initial condition for each committed dispatchable generator equal to the active set-points evaluated by the first stage;
2. Implement the day-ahead scheduled charge/discharge power of each ESS device;
3. Monitor RES power and load real-time data, and evaluate the unavoidable active power imbalance within the microgrid;
4. Read the cost coefficients of n_G DGs (i.e. $\alpha_{G,i}$, $\beta_{G,i}$, $\gamma_{G,i}$ for $i = 1,\dots,n_G$) collected into the SCADA system;
5. Solve the incremental costs (λ) and $P_{G,i}$ using the Eqns. (4)–(8);
6. Check the solution for lower and upper limit violations for $i = 1,\dots,n_G$. If n_{AP} generators are violating their active power limits, fix their active powers to their limits and go to (i), otherwise go to (7);
    - (i) Compute the new incremental cost (λ_{new}) and $P_{G,i}^{new}$ for $i = 1,\dots,N$ by Eqns. (9)–(11);
    - (ii) Check the new solution for lower and upper limit violations for $i = 1,\dots,N$. If there are other generators violating their active power limits, fix their active powers to their limits and come back to (i), otherwise go to (7);
7. Send the evaluated active power set-points to the local controllers of all committed DGs.

As can be noted, the proposed procedure runs continuously on the microgrid. Thanks to this characteristic, it is able to promptly reveal any power imbalances between scheduled levels of generation and load caused by forecast errors. Such imbalances are then recovered by rapidly adjusting the active power outputs of all available programmable sources.

4. Experimental tests

The proposed methodology was tested on the actual microgrid whose on-line diagram is shown in Fig. 3.

It consists of a low-voltage AC distribution network with a single transformer substation 20/0.4 kV located at bus 1, feeding several generation sources along with a Battery Energy Storage System (BESS) and two programmable loads. The main data of these components are summarized in Table 1.

More details on this system and its components can be found in [34].

In order to demonstrate the effectiveness of the proposed methodology, an experimental test was performed over a 24-hour period (from 10 a.m. of July 24, 2018 to the same hour of the following day). For this test case, programmable loads were used to generate the loading profile of a typical residential area characterized by about 250 houses. Moreover, the real-time behavior of a Jonica Impianti Jimp30 – 30 kW wind generator was emulated by means of the WTE.

To start up the algorithm day-ahead forecast of the load demand, RES power production and electricity market price shown in Figs. 4 and 5 were used.

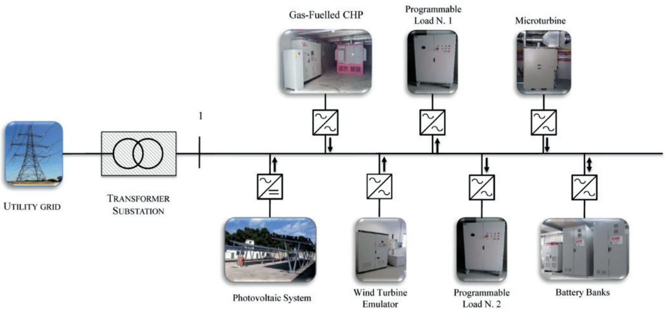

Fig. 3. The on-line diagram of the considered microgrid [33]

Table 1
Microgrid components characteristics

Microgrid components electrical characteristics			
Component	Nominal power [kW]	Maximum power [kW]	Minimum power [kW]
CHP [35]	120	0	120
Microturbine (MT) [36]	30	0	30
Photovoltaic system (PV)	50	0	50
Wind Turbine Emulator (WTE)	60	0	60
BESS [37]	60	0	60
Programmable load #1	120	0	120
Programmable load #2	120	0	120

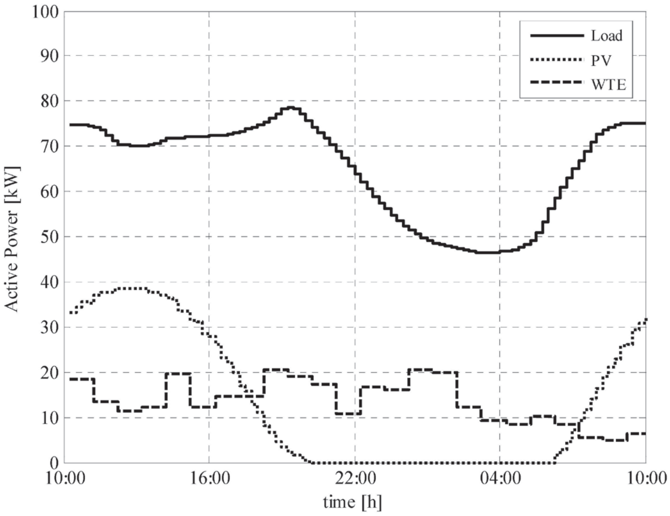

Fig. 4. The day-ahead forecast of the load demand, wind and photovoltaic

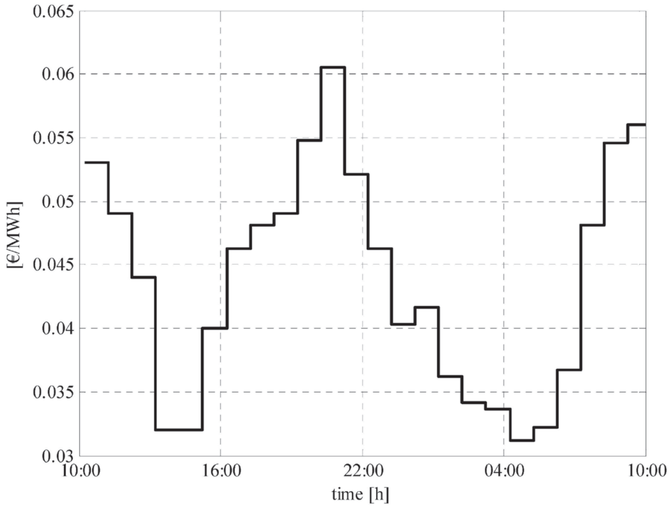

Fig. 5. Daily profile of the market price

Then, adopting the cost coefficients of the CHP, the MT and the BESS reported in [31] the economic dispatch was performed and the obtained results are shown in Figs. 6–8.

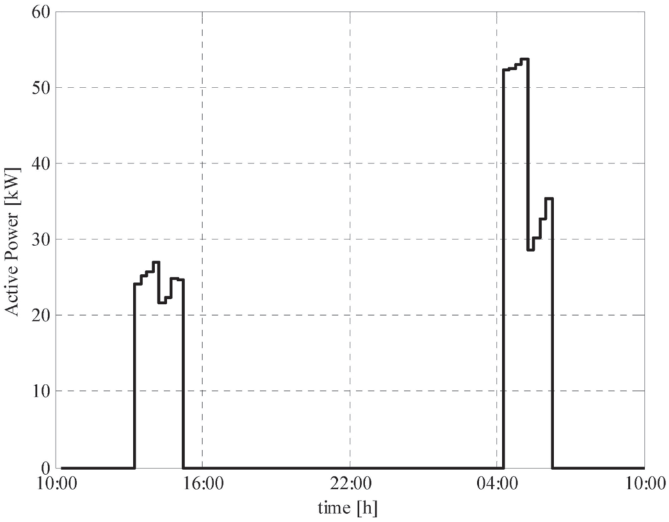

Fig. 6. The day-ahead schedule of the electric power exchanged with the utility grid through the tie-line switch (Q5N)

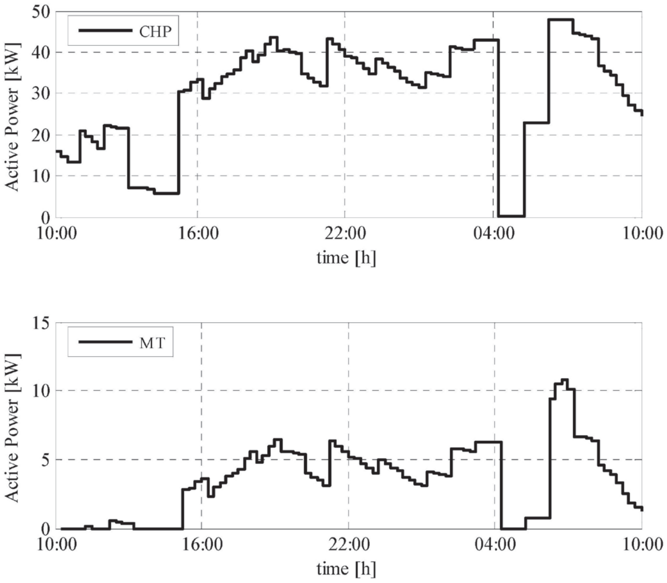

Fig. 7. Quarter-hour production plan of the CHP engine, the Microturbine

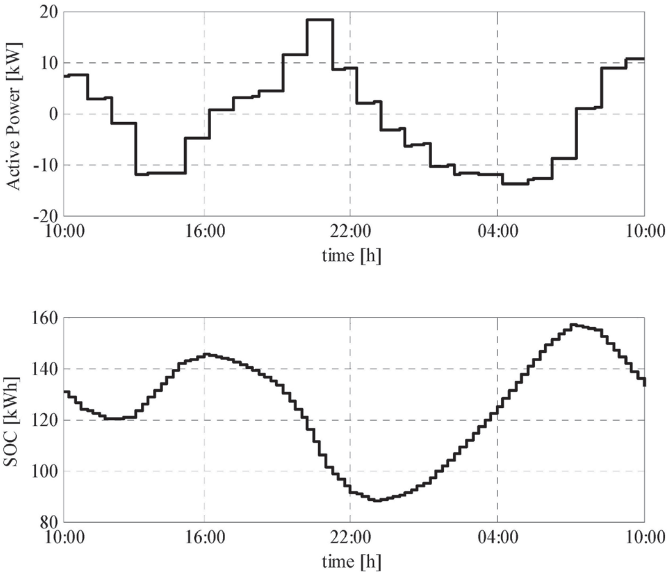

Fig. 8. Quarter-hour operation plan of the BESS

From the above figures, it is evident that the microgrid was scheduled to purchase energy when the electricity market price was low and to avoid exchanging power with the utility grid when the electricity price is high.

More specifically, during higher electricity market price, the CHP system was scheduled to provide its maximum active power for most of the time (Fig. 7). This was mainly due to its lower operating costs. On the contrary, the BESS was scheduled to be charged when the energy price is lower, and discharged when the price is higher. Moreover, it should be pointed out that charging/discharging schedules were determined in order to maintain the SOC of the BESS at the end of the day equal to the value at the beginning of the day.

Starting from these data, the on-line economic dispatch was implemented on the assumed microgrid.

The RES power and load real-time data as well as the actual active power exchanged with the utility are monitored by the EMS and their daily profiled are reported in Figs. 9 and 10.

Information is then processed by the EMS to renew the active power set-points of both CHP and MT so as to balance any discrepancies that arose between the actual tie-line power flow and its scheduled value. The obtained results are reported in Fig. 11. As can be noted, the proposed controller forced the CHP to provide its maximum allowed active power for the whole day, while the MT was called to provide the regulation service only when the CHP violated its limits.

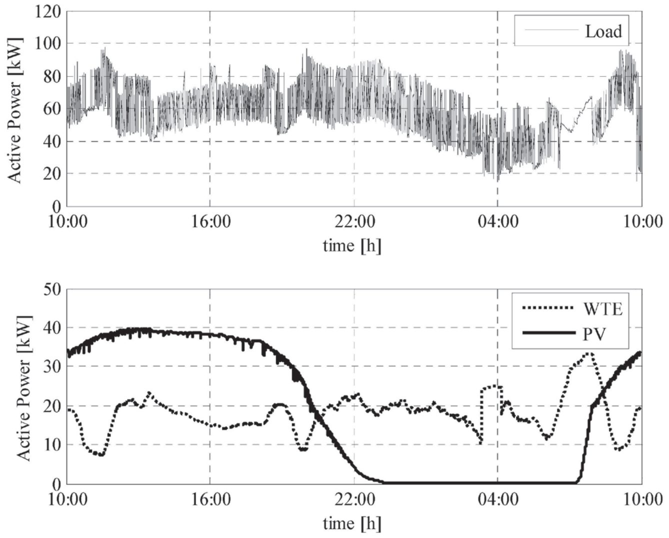

Fig. 9. Daily profiles of the load, the PV and the wind generation

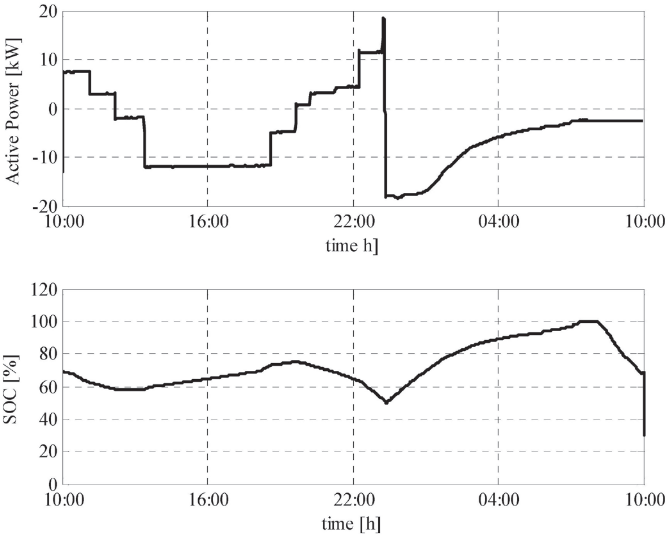

Fig. 10. Time-domain behavior of the active power output and SOC levels of the BESS

In order to give a qualitative measure of the correctness of the proposed methodology, a comparison between the actual power exchanged with the main grid and its scheduled value is presented in Fig. 12.

From this figure, it is evident that the actual tie-line power flow is always maintained near to its scheduled value (red line) except for the time period from 03:00 pm to 06:00 pm, when the BESS control switched from P-Q to the end-of-charge mode. In this case, the proposed controller promptly reacted sharing the control burden previously assigned to the BESS among the CHP and the MT. During another time period ranging from 04:00 am to 06:00 am the actual power exchanged with the utility grid strongly deviated from its scheduled one. This was mainly due to the greater availability of wind energy production compared to that forecasted.

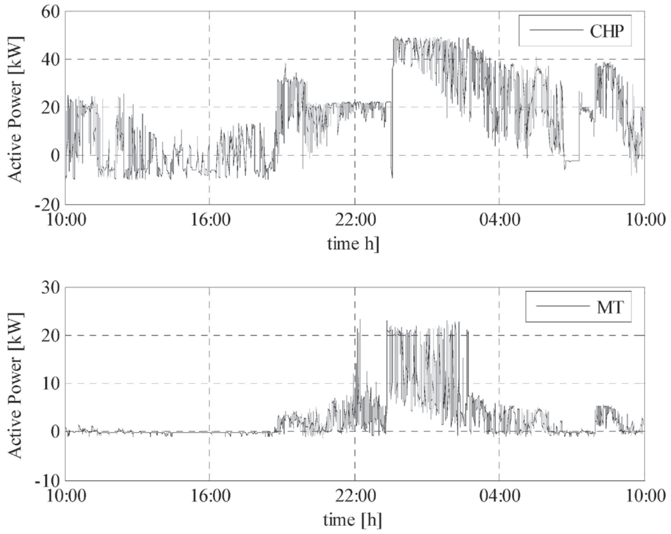

Fig. 11. Time domain behaviors of the active power outputs of both CHP and microturbine

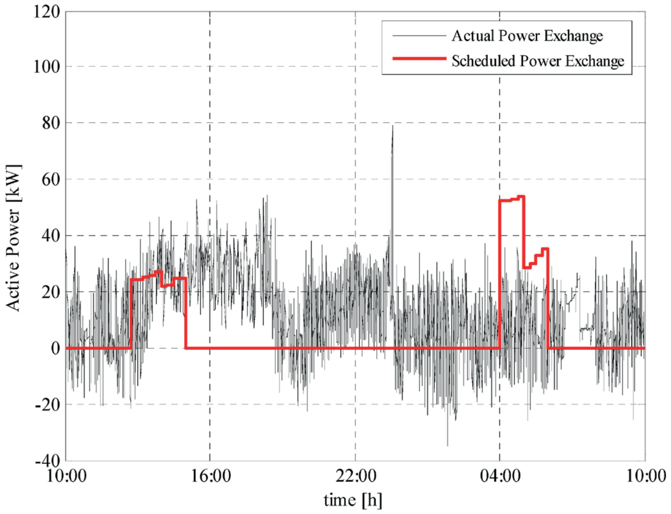

Fig. 12. Daily profile of the active power exchanged with the utility grid (PCC)

5. Conclusions and future work

In this paper, an online scheduling method has been developed to rectify the shortcomings of forecast-based production and meet the customers' needs.

The basic idea is to dispatch, in the on-line environment, the generation outputs to match power production to demand as closely as possible, while retaining the economy and security. An optimization problem consisting of two time parts has been developed for evaluating the optimal control actions.

The effectiveness of the proposed methodology has been tested experimentally on an actual microgrid. Experimental results showed that the controller is able to timely adjust the CHP system and microturbine outputs to reduce any system imbalances between the actual power exchanged with the utility grid and its scheduled value.

With this characteristics, the automatic controller demonstrated being able to follow the power exchange plan agreed with the utility grid thus avoiding high-energy penalties and additional costs.

Experiments also demonstrated the ability of the proposed controller to comply with the unavailability of the control action of one or more energy sources due to the saturation of their active power limits. In fact, in this case the controller fixed the active power of those sources violating constraints to their limits and then, automatically redistributed the control burden among the remaining generators that are committed in the regulation service, giving rise to a suboptimal condition.

Nonetheless, the performances of the proposed controller can be further improved by directly incorporating the BESS into the on-line economic dispatch. However, in order to ensure adequate power regulation, an additional objective function aimed to minimize deviations from the scheduled SOC of the day-ahead operation plan should be added in the optimization problem to limit the control action on the active power output of the BESS.

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