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An Optimization Algorithm for the Operation Planning of the University of Genoa Smart Polygeneration Microgrid

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Abstract

The aim of this paper is to describe the Smart Polygeneration Microgrid (SPM), which is being constructed at the Savona Campus of the Genoa University, also thanks to funding from the Italian Ministry of Education, University and Research (amount 2.4 Million Euros). Specifically, a detailed model of the grid is presented and an optimization problem is defined, in order to achieve suitable goals, like the minimization of the production costs or the maximization of power quality or environmental indices.

Introduction

The microgrid concept has been gaining a growing attention by many researchers worldwide, with significant activities carried out in the U.S., the E.U., Japan and Canada, where a number of demonstrator projects and test-bed facilities have been built in recent years.
As pointed out by Lidula et al. in [1], different strategies have been followed in developing the microgrid paradigm. In the U.S., the focus has been mainly put in exploiting the microgrid ability to operate in islanding mode in case of a grid outage or severe transient, switching from grid connected to islanding mode and vice versa in a seamless way, with the aim of increasing the supply reliability for loads. In Europe, the efforts have been primarily devoted to the integration of DERs (Distributed Energy Resources) and, in particular, renewable (non dispatchable) resources [2]. Other factors that have gained considerable attention are the reduction of network losses and the possibility to defer network upgrades [1].
The integration of DER, renewable ones in the first place, leads to a number of issues. First, random variability of solar radiation or wind speed in the hours to day timescale, makes it very difficult or impossible to follow a day-ahead production schedule; thus, a large penetration of renewable sources could lead to an increase of power system operational costs, due, for instance, to the augmented need of spinning reserve: as an example, in [3] the problem of costs related to the unpredictability of wind power production is addressed, with reference to the power system of Germany and Scandinavia, while in [4] the quantification of photovoltaic generation variability in various timescales has been extensively covered. Secondly, both renewable and classical DERs alter the distribution grid power flux, potentially leading to the deterioration of the voltage profile along, e.g., the interested feeder [5]: power injections can make the voltage rise beyond acceptable values at some of the feeder nodes. Classical regulation systems can hardly manage this occurrence, as they are designed to compensate for voltage drops along the line. Furthermore, rapid variations of the injected power (due to sudden changes of radiation [6] or wind speed), can cause disturbances (e.g. flicker) on the load voltage [5].
The microgrid concept, where loads, sources (both renewable and dispatchable) and storage systems coexist and are operated under a common management, is a possible solution for these problems.
In this context, the Smart Polygeneration Microgrid (SPM) of the Genoa University provides the possibility to go through all these issues both from a theoretical and from an experimental point of view, as it will give the potential for defining and experimentally validating new algorithms, logics and management strategies in order to provide useful solutions to the problem of the integration of DERs. The present paper, in particular, defines a static model of the SPM in order to optimize its steady-state working conditions to achieve some specific goals (e.g. economical or environmental) taking into account all the

constraints that ensure the desired level of power quality [7]. The paper is organized as follows: in section 2, the description of the SPM and of its main components is presented, while section 3 is devoted to the definition of the constraints necessary to set up the optimization procedure. The solution algorithm for the optimum problem is described in paragraph 4, while sections 5 and 6 are relevant respectively to the presentation of the results and to some concluding remarks.

SPM description

In this section the main components of the SPM are briefly described. An overview of the whole infrastructure [8] is given in Fig. 1.

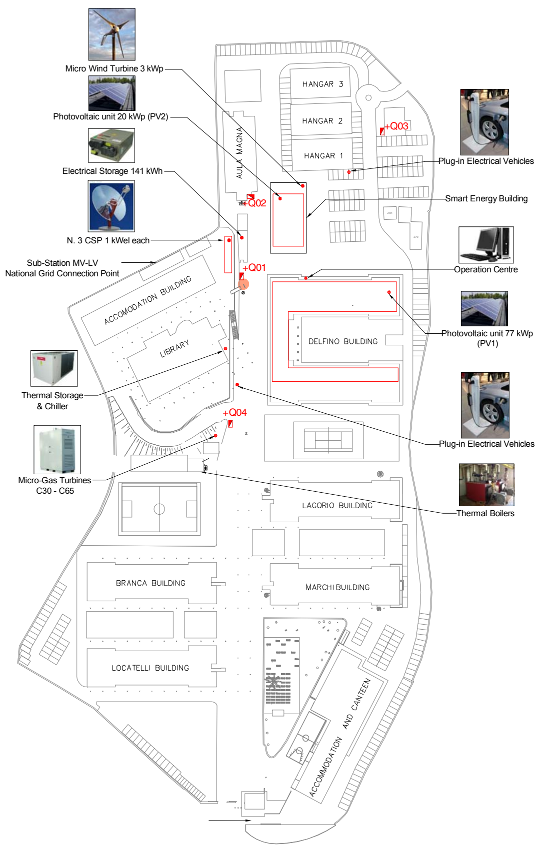

Fig. 1 Overview of the Savona Campus SPM

The system is fed by a MV/LV transformer substation (connected between bus 1 and bus 2 of Fig. 2). The three phase low voltage (400 V LL) distribution system is characterized by a 500 m long ring network, consisting of buses 2, 3, 4, 5 and 6. Its design guarantees the possibility of future expansions without increasing the size of the main electric switchboard, located in the electrical substation.

Bus 3 connects the main loads of the grid, namely the auxiliary services of the control room (CR) and is ready for the connection of the future Smart Energy Building (SEB, funded by the Italian Ministry of Environment with 3 Million Euros, deployed in 2014-15). Moreover, three concentrating solar power (CSP) generators equipped with Stirling engines (1 kW_e each) are located here.

Bus 4 is devoted to renewables, namely a photovoltaic field PV_1 (77 kW_e), a set of storage batteries (SB), with capacity of about 141 kWh_e and is ready to host two generating units: a 20 kW_e PV unit (PV_2) and a 3 kW_e wind turbine (WT), belonging to the future SEB.

Bus 5 connects an electrical vehicles charging station (EV_1), while bus 6 is devoted to the connection of two CHP gas microturbines (T_1-65 kW_e and T_2-28 kW_e)) and another electrical vehicles charging station (EV_2).

It should be observed that both the PV units, the wind turbine, the storage batteries and the two gas turbines are connected to the grid by means of an AC/AC converter; so they can generate also the desired reactive power belonging to a specified range, according to the Italian standard defined in [9].

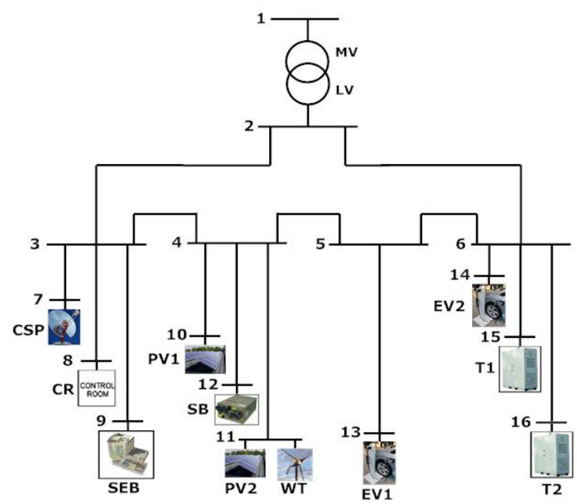

Fig. 2 Electric configuration of the SPM

SPM model for optimization problems

The optimization problem which can be set up on the SPM consists of finding out the time-profile of all the decisional variables in order to minimize (maximize) a specific objective function over time range [0, T_f]. Such decisional variables are:

- The reactive powers of all the devices connected to the grid by means of converters, $Q_{PV1}(t)$, $Q_{PV2}(t)$, $Q_W(t)$, $Q_{SB}(t)$, $Q_{T1}(t)$ and $Q_{T2}(t)$.
- The two gas turbines active power $P_{T1}(t)$ and $P_{T2}(t)$, as well as the active power exchanged by the storage batteries $P_B(t)$.

For the sake of clarity, all the active and reactive powers injected into the network will be considered as p.u. values, while the ones belonging to "device model equations" will be absolute values; anyway, the indication of the chosen base power S_b will be provided in all the equations to avoid misunderstandings.
Of course, in order to ensure a solution for the problem, one should know the time behavior of the following input data in the interval $[0,T_f]$:

- Solar irradiance $Irr(t)$
- Absolute temperature $T(t)$
- Wind speed $V_w(t)$
- SPM electrical load profiles $P_{CR}(t)$, $Q_{CR}(t)$, $P_{SEB}(t)$, and $Q_{SEB}(t)$
- Campus thermal energy request per time unit $P_{Dth}(t)$

The knowledge of the first three quantities allows to estimate (at any time) the active power production of PV units $P_{PV1}(t)$ and $P_{PV2}(t)$ (see [10-11] for details), wind turbine $P_W(t)$ (see [12-13] for details) and CSP $P_{CSP}(t)$, while the thermal demand is necessary to establish a thermal energy balance, in our case reflecting the fact that the productions $P_{T1th}(t)$ and $P_{T2th}(t)$ of the two microturbines are used to contribute satisfying the Campus thermal request, together with a boiler, whose thermal power is labelled as $P_{boiler}(t)$.
The constraints of the optimization problems, which should be satisfied at any time t in the interval $[0,T_f]$, are of three kinds: electric power balance constraints, power quality constraints and specific devices constraints.

Electric power balance constraints

Such constraints are basically the load flow equations, expressing the power balance at each of the N_b buses of the grid: for any $h = 1,\ldots,N_b$

$$P_h(t) + \mathrm{j}Q_h(t) = V_h(t)e^{\mathrm{j}\delta_h(t)}\sum_{r=1}^{N_b} Y_{hr}^* V_r(t)e^{-\mathrm{j}\delta_r(t)} \tag{1}$$

being $P_h(t)$ ($Q_h(t)$) the p.u. active (reactive) power injection at bus h, while $V_r(t)e^{\mathrm{j}\delta_r(t)}$ the p.u. voltage phasor at bus r and Y the network admittance matrix.

Power quality constraints

They express the fact that currents flowing in all the N_L lines must not exceed their rated values and voltages must belong to a specified range, namely: for any $k = 1,\ldots,N_L$

$$\left|\dot{I}_k(t)\right| = \left|\frac{\sum_{h=1}^{N_b} A_{kh}\dot{V}_h(t)}{\dot{z}_k}\right| \le I_{\max,k} \tag{2}$$

and for any $h = 1,\ldots,N_b$

$$0.95 \le \left|V_h(t)\right| \le 1.05 \tag{3}$$

being $\dot{z}_k$ the longitudinal impedance of the k^{th} interconnection and A_{kh} the element in position (k,h) of the nodal incidence matrix A.

Specific devices constraints

First of all, one should specify the limits on the power factor of all the devices connected by means of a power electronic converter, which, as specified in [9], are expressed by the following relationships and can be represented in the P-Q plane as in Fig. 3 (at least for the static generators):

$$\begin{gathered} -\sqrt{A_i^2 - S_bP_i(t)^2} \le S_bQ_i(t) \le \sqrt{A_i^2 - S_bP_i(t)^2} \\ -A_i\cos\varphi_{i,\min} \le S_bQ_i(t) \le A_i\cos\varphi_{i,\min} \end{gathered} \tag{4}$$

being respectively P_i, Q_i, A_i and $\cos(\phi_{i,\min})$ the p.u. active power, p.u. reactive power, the rating and the minimum allowable power factor of the device i.

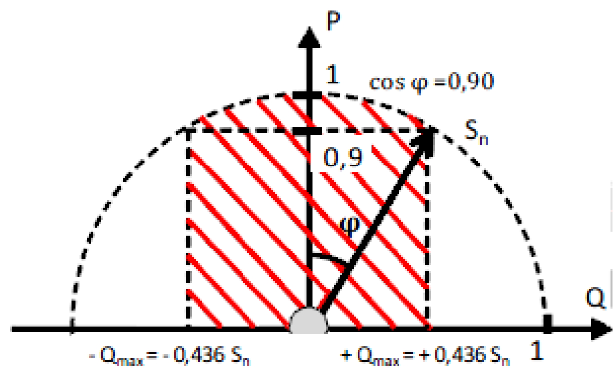

Fig. 3: capability curve for static generators according to [9]

Moreover, the following storage battery model equations have to be inserted, linking the p.u. active power injection $P_s(t)$ with the energy $W_b(t)$ stored in the batteries

$$S_bP_s(t) = \begin{cases} P_b(t)\eta_{out} & \text{if} \quad P_s(t) \ge 0 \\ P_b(t)/\eta_{in} & \text{if} \quad P_s(t) < 0 \end{cases} \tag{5}$$

$$P_b(t) = -\frac{dW_b(t)}{dt} \tag{6}$$

$$\begin{cases} -P_{b,\max} \le P_b(t) \le P_{b,\max} \\ W_{b,\min} \le W_b(t) \le W_{b,\max} \end{cases} \tag{7}$$

being $P_b(t)$ the power recharging/discharging the battery, η_{out} (when discharging) and η_{in} (when recharging) two suitable efficiencies and equation (7) stating the physical limits of batteries power and energy.
Then, one has to account the following gas turbine model equations:

$$P_{thTi}(t)=S_b P_{Ti}(t)\cdot\frac{P_{thTi,rated}}{P_{Ti,rated}} \quad (8)$$

which expresses the link between electric active power P_{Ti} and thermal power P_{thTi} of the i^{th} (i=1,2) gas turbine, by means of the ratio between their rated values $P_{Ti,rated}$ and $P_{thTi,rated}$.

Finally, the following thermal energy balance must be considered, once given the Campus thermal demand $P_{D,th}$, as a function of time:

$$P_{boiler}(t)+P_{th,T1}(t)+P_{th,T2}(t)\ge P_{D,th}(t) \quad (9)$$

Objective function

The optimization problem formulation is complete once one has defined a suitable objective function. Here, results will be shown regarding the minimization of the overall cost, defined as:

$$C_{TOT}=\int_{[0,T_f]}\left[C_T(t)+C_B(t)+C_N(t)\right]dt \quad (10)$$

being respectively $C_T(t)$, $C_B(t)$ and $C_N(t)$ the unit time costs related to the turbine production, the boiler thermal energy generation and the network energy exchange, respectively. Each quantity is defined by means of the following relationships [8]:

$$C_B(t)=\frac{P_{boiler}(t)}{\eta_{boiler}}TES_{pp} \quad (11)$$

whit TES_{pp}=0.09 €/kWh$_{PE}$ and η_{boiler} =0.9;

$$C_N(t)=\begin{cases}\pi_p(t)P_1(t)S_b & \text{if } P_1(t)\ge 0\\ \pi_s P_1(t)S_b & \text{if } P_1(t)<0\end{cases} \quad (12)$$

Where P_1 is the active power injected at bus 1, while $\pi_p(t)$ and π_s are the purchasing and selling prices of the electric energy exchange with the network, respectively, in this context we supposed $\pi_p(t)$ time independent and equal to 0.256 €/kWh while $\pi_s=0.07$ €/kWh;

$$C_T(t)=\sum_{i=1}^{2}\frac{S_b P_{Ti}(t)}{\eta_{el,i}(t)\cdot LHV}\cdot CNG_i(t) \quad (13)$$

where

$$CNG_i(t)=\left(0.22\cdot\eta_{el,i}(t)\cdot LHV\right)\cdot\left(NG_{ppwf}-NG_{pp}\right)+NG_{pp} \quad (14)$$

with LHV=9.7 kWh$_{PE}$/m^3, NG_{pp} =0.70 €/m^3 and NG_{ppwf} = 0.43 €/m^3, and the turbine efficiency $\eta_{el,i}$ at any load condition is defined as a function of its efficiency under rated conditions $\eta_{el\_full,i}$ by means of the following relation

$$\eta_{el,i}(t)=\eta_{el\_full,i}\cdot\eta^*_{el,i}(t) \quad (15)$$

being

$$\eta_{el\_full}=\begin{cases}\eta_{el\_max} & \text{if } T\le -2°C\\ bT+c & \text{if } -2°C<T\le 50°C\end{cases} \quad (16)$$

$$\eta^*_{el,i}(t)=a_0\ln\left(\frac{S_b P_{Ti}(t)}{P_{Ti,full}(t)}\right)+a_1 \quad (17)$$

with b, c, a_0 and a_1 suitable coefficients [14-15] and P_{Ti_full} is related to the rated power according to

$$P_{Ti\_full}(t)=\begin{cases}P_{Ti,rated} & \text{if } T(t)\le T_{min}\\ P_{Ti,rated}\left(1+\frac{T(t)-T_{min}}{T_{max}-T_{min}}a_2\right) & \text{if } T_{min}<T(t)\le T_{max}\end{cases} \quad (18)$$

being T_{min}=21°C and T_{max}=50°C, and a_2 a coefficient [14-15].

Numerical solution of the optimized problem

If we sample the range of interest in N_T +1 time intervals of size $\Delta t=T_f/N_T$ according to the following rule

$$t_n=(n-1)\Delta t, \qquad (n=1,\ldots,N_T+1) \quad (19)$$

one can transform the above constraints in a discrete form as explained in the following. Let us indicate with x the unknowns vector, which, for each time sample, consists of N=2N_b+11 components containing the amplitude and phase angles of all the bus voltages as well as all the decisional variables described in the previous section. As a consequence, x presents $N(N_T$+1) elements ordered as follows:

$$\begin{aligned}
&V_h(t_n)=x_{h+N(n-1)} \qquad h=1,\ldots,N_b\\
&\delta_h(t_n)=x_{N_b+h+N(n-1)} \qquad h=1,\ldots,N_b\\
&Q_{PV1}(t_n)=x_{2N_b+1+N(n-1)}\\
&Q_{PV2}(t_n)=x_{2N_b+2+N(n-1)}\\
&Q_W(t_n)=x_{2N_b+3+N(n-1)}\\
&P_b(t_n)=x_{2N_b+4+N(n-1)}\\
&W_b(t_n)=x_{2N_b+5+N(n-1)}\\
&Q_S(t_n)=x_{2N_b+6+N(n-1)}\\
&P_{T1}(t_n)=x_{2N_b+7+N(n-1)}\\
&Q_{T1}(t_n)=x_{2N_b+8+N(n-1)}\\
&P_{T2}(t_n)=x_{2N_b+9+N(n-1)}\\
&Q_{T2}(t_n)=x_{2N_b+10+N(n-1)}\\
&P_{boiler}(t_n)=x_{2N_b+11+N(n-1)}
\end{aligned} \quad (20)$$

As a consequence, for any time sample t_n (with $n=1,\ldots,N_T+1$), it follows that:

-) the phasor of the voltage at any bus $h=1,\ldots,N_b$ is given by

$$\dot{V}_h(t_n)=x_{h+N(n-1)}e^{jx_{h+N_b+N(n-1)}} \quad (21)$$

-) the load flow equations (1) at any bus $h = 1,\ldots,N_b$ can be rewritten as

$$\dot{S}_h(t_n) = \dot{V}_h(t_n) \sum_{r=1}^{N_b} \left[\dot{Y}_{hr} \dot{V}_r(t_n) \right]^* \tag{22}$$

-) the quality constraints (2), at any line $k = 1,\ldots,N_L$ becomes

$$\left| \dot{I}_k(t_n) \right| = \frac{S_b}{\sqrt{3} V_b} \left| Y_{long,kk} \sum_{h=1}^{N_b} A_{kh} \dot{V}_h(t_n) \right| \le I_{\max,k} \tag{23}$$

-) the quality constraints (3) at any bus $h = 1,\ldots,N_b$ becomes

$$0.95 \le x_{h+N(n-1)} \le 1.05 \tag{24}$$

-) the discretization of (4) is straightforward

-) the storage equations can be approximated as

$$P_b(t_n) = \frac{W_b(t_n) - W_b(t_{n+1})}{\Delta t}$$
$$-P_{b,\max} \le P_b(t_n) \le P_{b,\max} \tag{25}$$
$$W_{b,\min} \le W_b(t_n) \le W_{b,\max}$$

-) the turbine-boiler models can be discretized simply by sampling equations (8)-(9).

Finally, the objective function can be approximated evaluating the integral appearing in (10) with the simplest quadrature rule, as follows:

$$C_{TOT} \simeq \sum_{n=1}^{N_T} \left[C_T(t_n) + C_B(t_n) + C_N(t_n) \right] \Delta t \tag{26}$$

Numerical simulations

In this section, the results of some numerical tests performed on the SPM are reported. The considered timeframe is one day, sampled in 24 time steps (i.e. hour by hour). The main assumption is the knowledge of the time profile of solar irradiance, ambient temperature, wind speed and thermal and electric load. As a consequence, one knows the waveform of the PV units production, which is depicted in Fig. 4, of the electric loads of the SPM ring (whose sum is depicted in Fig. 5) and of the Campus thermal load, represented in Fig. 6. For the sake of brevity, both the CSP and the wind turbine production are not represented in the following graphs, as their rating is much smaller than the other sources.

The optimized daily operation of the SPM allows to save about 200 euros with respect to the as-is situation in which the SPM is absent (from about 1700 euros to about 1500 euros). Analysing more in details the results, one can notice the fact that in night time (0-5) the thermal demand is very low and is basically satisfied by the gas turbines, which produce the quantity of energy necessary not to resort to the boiler.

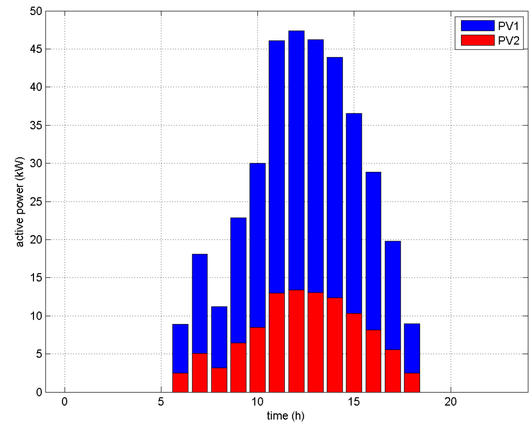

Fig. 4: Superimposed data series of PV units production.

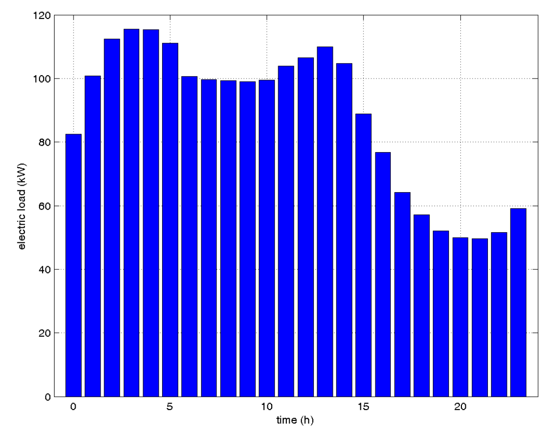

Fig. 5: SPM electric load

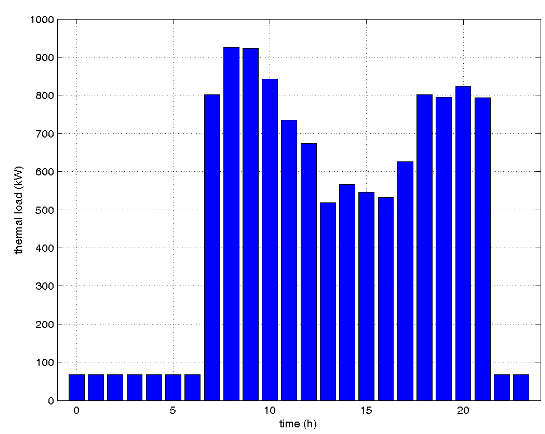

Fig. 6: Campus thermal load

As a consequence, the linear relationship between thermal and electric production of the gas turbines eq. (8) fixes the produced active power (Fig. 7), which is not able to cover the entire electric request, demanding to the network the electric power balance (Fig. 8). On the contrary, during daytime the overall load is satisfied by the SPM DERs, thus resulting in a practically negligible active power exchange with the network.

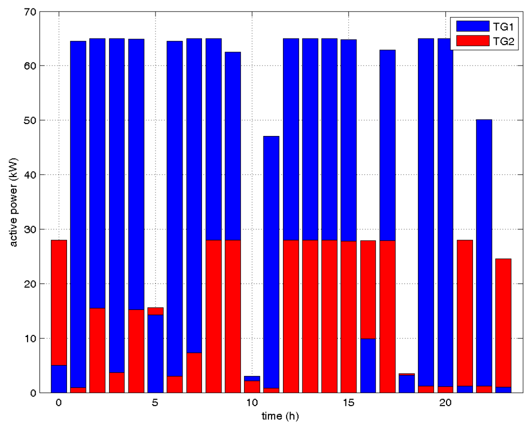

Fig. 7: Superimposed data series of gas turbines active power

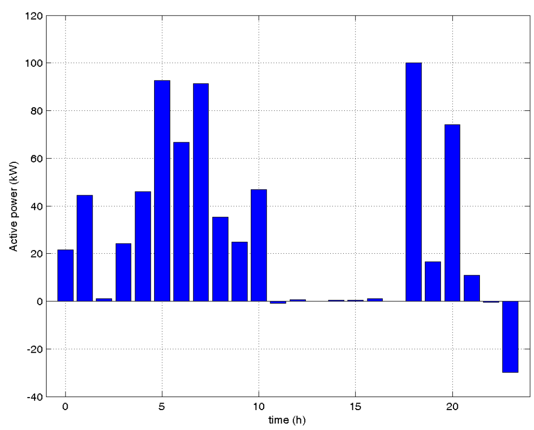

Fig. 8: Network injected active power

Moreover, the boiler power profile (Fig. 9) verifies the above considerations about night-time, while shows that the boiler is on during the day, as the thermal request is higher than the maximum production of the two turbines.

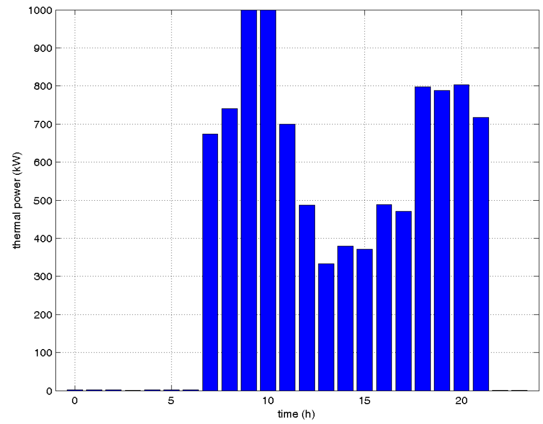

Fig. 9: Boiler thermal power production

Figures 10 and 11 depict respectively the storage power and energy (assuming that the storage system is full at the beginning of our analysis); comparing them it is possible to verify equation (6), as if in one hour the injected power is positive, the next hour energy content of the storage system will be smaller than the previous one (which is correct, if one remembers the approximation of the time derivative with the incremental ratio calculated in the first line appearing in equation (25)).

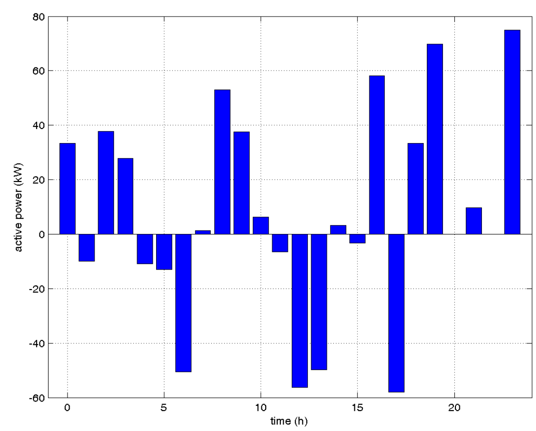

Fig. 10: Active power injected by the storage system

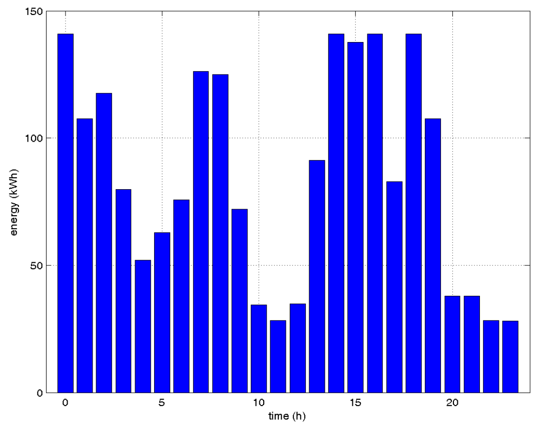

Fig. 11: Energy content of the storage system

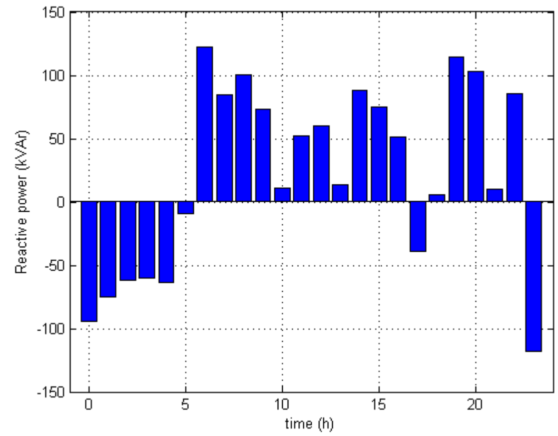

Fig. 12: Reactive power exchange with the external network

From the reactive powers standpoint, if one examines Fig. 12 which shows the reactive power exchange with the external network, two main considerations arise:

- during nighttime, especially between midnight and five, no renewable resources are present and, since the gas turbines are not sufficient to satisfy the loads, the network has to provide the missing active power. This would imply some positive voltage drop along the cables, as in the common situations of radial grids. In this case, the optimum procedure requires that the SPM provides some reactive power to support the voltage and so the overall system behaves like a capacitor at the PCC, without needing any specific reactive power compensator.

- During daytime, especially between 10 and 3 PM, since the active power exchange with the external network is practically zero, voltage would increase; the algorithm makes the SPM absorb some positive reactive power in order to maintain the voltages to a value which is as close as possible to 1 p.u. As a matter-of-fact, this is exactly what is required by the majority of grid codes (see [9] as an example).

The result of this action is that all the voltages are practically 1 p.u. both in night time and in daytime; here, for the sake of brevity, the voltage at bus 10 is only plotted (Fig. 13), which is the one presenting the highest deviation from its rated value.

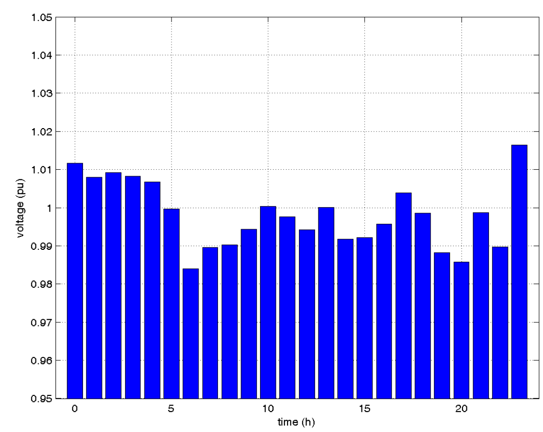

Fig. 13: Voltage at bus 10

Conclusions

In this paper, the Smart Polygeneration Microgrid (SPM), which is being constructed at the Savona Campus of the Genoa University has been described and an optimization algorithm has been presented for steady-state electrical and thermal analysis. The results have highlighted the fact that an optimized operation of the Microgrid allows to save about 20% money. Future work will concern the possibility of removing the assumption of "perfect" knowledge of the daily load profiles and renewables production, and so of inserting some probabilistic analysis in the implementation of the optimum algorithm. Moreover it would be useful to analyse in a deeper way the mathematical properties of the problem, so as to reduce the CPU effort; more in details, the whole problem differs from 24 separate optimization problems because of the storage model that relates only the storage energy contents in two subsequent hours. This suggests the possibility of considering three or four shorter timeframe optimization problems and verifying if this new configuration (which should be better in terms of computational issues) provides an optimum point sufficiently close to the one obtained analysing the whole day.

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