ENERGY PLANNING APPROACH FOR AN EFFICIENT DISTRIBUTION GRID

Maurizio DELFANTI
Politecnico di Milano – Italy
maurizio.delfanti@polimi.it

Davide FALABRETTI,
Politecnico di Milano – Italy
davide.falabretti@polimi.it

Stefano MANDELLI
Politecnico di Milano – Italy
stefano.mandelli@polimi.it

Marco MERLO
Politecnico di Milano – Italy
marco.merlo@polimi.it

Matteo MONCECCHI
Politecnico di Milano – Italy
matteo.moncecchi@mail.polimi.it

ABSTRACT

The work proposes a novel planning procedure to design the portfolio of Dispersed Generation in a given area in order to exploit optimally the locally available RES. The objective of the work is to provide suitable indications to Policy Makers useful to develop more effective regional energy plans. The developed approach is applied on a real life study case: the electric distribution network supplying the urban area and the neighbourhood of the Italian city of Aosta.

1. INTRODUCTION

Nowadays, it is well accepted that the concept of electricity chain, as traditionally structured (production, transmission and distribution of electricity), is changing. Actually, new actors are appearing in the electric power system. Renewable Energy Sources (RES), storage apparatuses, e-mobility are driving to new opportunities, but also new issues, about the planning and control of electric grids, in particular at distribution level (the one devoted to host Dispersed Generation: DG). Several works in the technical literature investigate problems related to the electric grid [1] and propose possible solutions [2]; vice-versa, it is more complex for Policy Makers to propose rules able to properly drive the change.

Starting from this background, the work describes and applies an energy planning procedure designed to promote an efficient development of DG in a given area. The proposed procedure adopts a bottom-up approach, designing the energy portfolio from the local scale perspective, which takes full advantage from the locally available RES. In fact, a main issue to consider in the deployment of DG on distribution systems is that electrical networks, especially at MV/LV level, are able to accept a limited amount of local generation. Therefore, in areas with great penetration of DG (as the Italian Alpine Space [3]), it is important to select in advance the RES to promote, in order to drive the maximum benefits (e.g., to reduce at best the dependency from fossil fuels) with the minimum impact on the electric grid.

The paper is organized as follows. In Section 2, the approach proposed and the mathematical formulation adopted to identify the optimal DG portfolio in a given area are depicted. Section 3 reports the numerical results obtained in a typical application scenario, the Italian city of Aosta, an area with great penetration of RES generation, mainly hydro. Finally, in Section 4, some conclusions are provided.

2. THE APPROACH PROPOSED

The final goal of the procedure developed in the work is to identify the optimal DG portfolio, both in terms of quantity (new capacity installed, in MW) and primary source technology, to fit at best the local energy needs, i.e. to cover the load minimizing the mismatch between generation and production. The optimal mix of DG power plants, according to this approach, is the one able to minimize the amount of energy absorbed by the HV network, avoiding at the same time to produce electrical energy locally when it is not needed, i.e. by limiting the Reverse Power Flow (RPF) measured at the HV/MV interface in Primary Substation (PS). To this purpose, the procedure needs the following inputs:

- the yearly power profile of the overall load supplied by the PS;
- the yearly power profile of each DG technology considered.

Figure 1 and Figure 2 show, for example, the power profile of PV and wind sources (these are some of the profiles considered in the following numerical analyses; see Section 3).

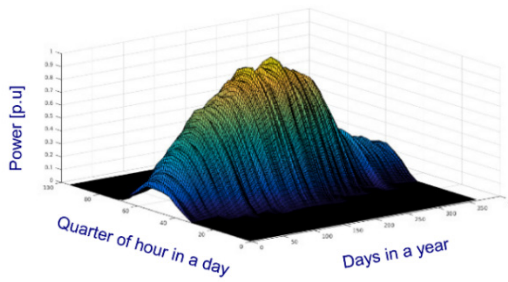

Figure 1. Energy maps of the yearly PV source (in p.u. w.r.t. the DG plant rated power).

Data are reported as energy maps: i.e., instead of representing the DG production with the conventional two-dimensional profile (power, or hourly energy, as a function of time), a three-dimensional representation is used, in which the production is reported as a function of both the time of day and the day of the year.

This allows to show the whole yearly profile as a surface, highlighting possible daily, weekly and seasonal trends. The yearly energy production for the two RES depicted in Figure 1 and Figure 2 could be quite similar in the considered scenario, but it is clear that their instantaneous behaviour is very different. So, the impact on the electric network (for example, in terms of load degree of conductors or possible overvoltages) is also very different.

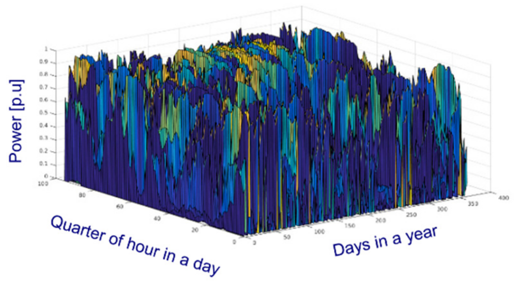

Figure 2. Energy maps of the yearly wind source (in p.u. w.r.t. the DG plant rated power).

In this work, the optimal DG portfolio, allowing to best fit the energy needs of local load, is identified through an optimization process based on the minimization of the least mean square error of the energy balance. To this purpose, a commercial mathematical tool for the quadratic optimization is used (Matlab software package). Within the tool, the objective function (i.e. the quantity to minimize) is formulated according to the following syntax:

$$\min \frac{1}{2} \cdot x^T H x + f^T x \tag{1}$$

Eq. (1) is subjected to the following constraints:

$$\begin{cases} \overline{A}_{eq} \cdot x = b_{eq} \\ lb \le x \le ub \end{cases} \tag{2}$$

Therefore, by suitably defining the quantities in eq. (1) and eq. (2), it is possible to identify the portfolio of DG power plants able to satisfy the load consumption of the PS under analysis through local production, taking into account at the same time the technical constraints (RPF) acting on the network. As already mentioned, the amount of energy produced by new DG power plants is an input of the procedure and is set so as to satisfy a given yearly percentage of the energy required by the load (changing from 10 to 150%). Therefore, a different optimal DG portfolio is identified according to the amount of load to supply by the local generation. In detail, for the specific problem under analysis, the general formulation of eq. (1) is expressed as:

$$\min \sum\nolimits_{year} \mathrm{Res}(t)^2 \tag{3}$$

Where *Res(t)* is assumed as the energy flow, for each time sample, through the main grid, i.e. the energy unbalance between load and generation of the area under study. Therefore, the matrix H and the vector f are defined as:

$$\overline{H} = \begin{bmatrix} 2\sum_{year} Gen_1(t)Gen_1(t) & \dots & 2\sum_{year} Gen_1(t)Gen_{DGtech}(t) & 0 \\ \vdots & \ddots & \vdots & 0 \\ 2\sum_{year} Gen_6(t)Gen_1(t) & \dots & 2\sum_{year} Gen_6(t)Gen_{DGtech}(t) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

$$\bar{f} = \begin{bmatrix} -2\sum_{year} Load(t)Gen_1(t) \\ \vdots \\ -2\sum_{year} Load(t)Gen_{DGtech}(t) \\ \sum_{year} Load(t)^2 \end{bmatrix} \tag{5}$$

In eq. (1), x represents the vector of unknowns, which, determined in output to the optimization problem, minimizes the objective function: i.e., in the problem under analysis, the vector x is the optimal DG portfolio connected to the grid in the ideal scenario, in terms of overall rated power of the power plants shared for DG technology.
Bounds of eq. (2) are used to properly take into account the correlation between the size of DG power plants and technology of the RES exploited. The first constraint of eq. (2) is used to force a given rate of DG penetration, in terms of yearly energy produced by the power plants connected to the grid:

$$\overline{E} \cdot \overline{P} = \sum\nolimits_{i=1}^{DGtech+1} E_i \cdot P_i = E_{DG} \tag{6}$$

The elements of E in eq. (6) represent the amount of energy to produce locally with a given DG technology, while P is the power of DG plants to connect to the main grid for each DG technology. This power is subject to the maximum and minimum bounds of eq. (2):

$$P_i^{\min} < P_i < P_i^{\max} \tag{7}$$

The results of the optimization process potentially could be greatly affected by the load and generation profiles considered in input to the procedure. Therefore, in the study, a sensitivity analysis is performed to assess the rate of change of the selected optimal portfolio according to variations of the DG profiles. The analysis provides an iterative process, in which at each step the DG energy maps are perturbed, eventually checking the results of the optimization process (optimal DG portfolio). The procedure stops when the power of each technology of the portfolio converges to a given value (i.e. when the mean value of the power for each technology changes from an iteration to the next one less than 0.05%).

To the just mentioned purpose, different parameters of the production profiles are perturbed.

- Amplitude: the values of production in a given time slot (15 min.) are perturbed introducing a normal or random noise distribution.
- Hourly time shift: the power profiles are shifted forward or backward of a random time, up to 1 h.
- Daily time shift: the power profile is shifted forward or backward in time up to 4 days.

The sensitivity analysis carried out is used to evaluate the robustness of the procedure with respect to the input adopted and to evaluate the degree of confidence of results.

3. NUMERICAL ANALYSES ON THE CITY OF AOSTA

The proposed procedure, aimed to support Policy Makers in defining the best strategy to foster the spreading of DG, has been applied to a real scenario: the urban area of Aosta, the chief town (population of 35 000 inhabitants) of the Valle d'Aosta region, in the Northwest of Italy. Figure 3 reports the political border of Aosta city, which influences the energy needs evaluated in the paper, i.e. the energy flow on the HV/MV substation is also relevant to the suburban areas of the city.

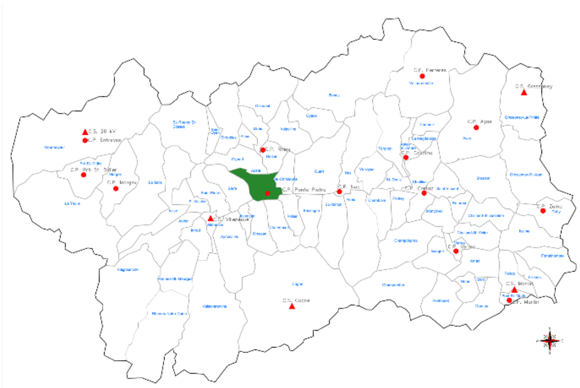

Figure 3. Aosta city area (green) and the electrical HV/MV substations in the Valle d'Aosta region (red).

The MV network supplying this area has a radial structure, starting from a HV/MV primary substation equipped with two 132/15 kV transformers, each one rated 25 MVA. The considered scenario refers to an urban area in a mountain region, where there is great availability of RES. A metering campaign is available: real production/consumption measures collected in the area under analysis over a whole year, and the energy flows measured each 15 minutes in the HV/MV station. RES production profiles are supposed to be equal to existing generators, subdivided with respect to the primary resource exploited (PV, wind, etc.). The following DG technologies are considered: 1. PV; 2. wind; 3. mini hydro; 4. medium hydro; 5. industrial CHP; 6. district heating CHP.

Figure 4 shows the energy map of the yearly load profile for the network under study (positive values mean power absorbed from the HV system). The energy map is related to the on-field measurements taken in the Aosta PS during year 2014. As one can observe, the profile has the typical load trend with two peaks, in the morning and in the evening. Moreover, as typical in the mountain regions, the winter energy needs are predominant. Figure 5 reports the results of the analysis performed to identify the optimal DG portfolio: i.e., for a percentage of load supplied by local DG ranging from 0 to 150%, the optimal power of each DG technology best fitting the PS load profile is shown.

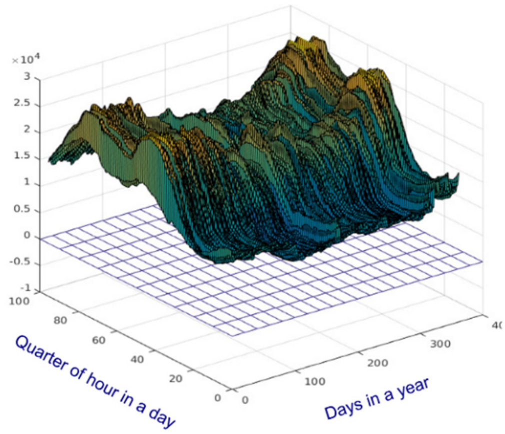

Figure 4. Energy map of the yearly load profile of the PS of the Aosta city (W).

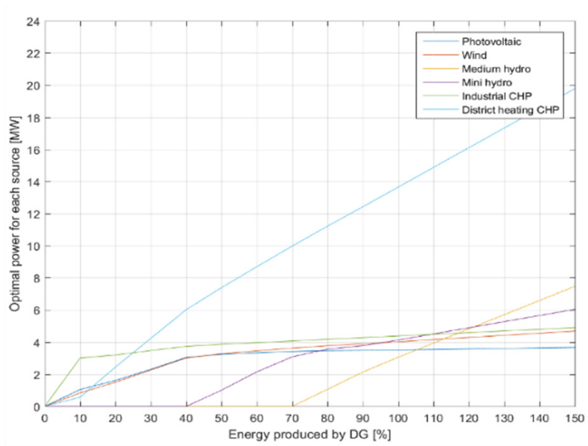

Figure 5. Optimal DG portfolio (MW), according to percentage of load supplied by local generation.

One can observe that industrial CHP (green line) is the first resource to be selected, but, consequently to its power profile, it quickly saturates and, for DG energy penetration greater than 10%, district heating resources are selected. Wind and PV generators are also selected, but with lower shares. Finally, mini and medium hydro generators are selected only in case of high DG penetration (greater than 40 and 70% of the yearly energy needs, respectively).

Table 1 reports the results of the sensitivity analysis performed. More in detail, the mean and standard deviation values are obtained introducing on the DG power profiles the perturbations depicted in Section 2, considering different DG penetration rates. As highlighted, although variations on the DG energy maps affect the outputs of the procedure, the impact is quite limited; so, it is possible to state that the results have a general meaning.

RES	Mean / Std. Dev.	DG penetration						
		20%	40%	60%	80%	100%	120%	140%
1	μ	1613	3049	3335	3466	3510	3573	3637
	σ	1129	1149	1161	1174	1181	1189	1199
2	μ	1503	3012	3456	3773	4023	4289	4555
	σ	267	337	399	428	444	467	491
3	μ	0	0	34	1061	3059	4825	6592
	σ	0	0	208	963	827	915	1007
4	μ	0	1	2151	3567	4128	4893	5658
	σ	0	11	249	937	839	935	1036
5	μ	3197	3736	3967	4174	4382	4591	4799
	σ	945	868	832	811	797	783	769
6	μ	2448	6021	8697	11220	13652	16106	18560
	σ	144	130	126	126	118	118	119

Table 1. Sensitivity analysis on the DG portfolio (kW).

Finally, Figure 6 shows some parameters representative of the PS behaviour as seen from the HV system: the maximum power injected by the MV grid in the HV system in RPF conditions (a), evaluated over a whole year, and the overall yearly time during which the RPF condition is assessed (b). Both quantities are reported as a function of the percentage of load supplied through the DG power plants connected on the distribution network. Each graph details the box plot for a particular DG penetration (mean value, standard deviation, and min. and max. of all data are reported).

Figures highlight that, up to an energy produced by DG equal to, or lower than, 30-40% of load, no RPF occurs toward the HV system. Increasing the DG penetration, a RPF condition is obtained, and, even, a more than linear increase of the maximum power injected in the main grid is observed. Such working conditions are commonly identified as the ones in which Smart Grids approaches are required to guarantee the reliability of the grid and the security of supply. Consequently, in the perspective of the paper, the Policy Maker could define, with the local DSO and national TSO, adequate bounds (e.g. maximum RPF occurrence in a year), and consequently to identify the maximum DG penetration acceptable in the area, in compliance with the electric system requirements. For such a total DG penetration level, the procedure proposed provides to the Policy Maker the optimal generation portfolio for a given local area.

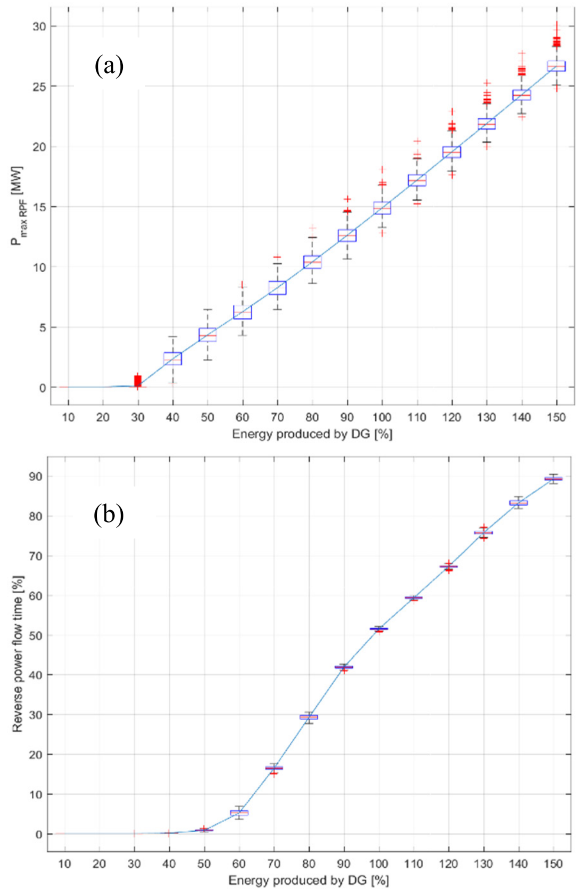

Figure 6. RPF at the HV/MV interface, according to the load (%) supplied by the DG: (a) Maximum RPF power (MW); (b) yearly RPF time (%).

4. CONCLUSION

The paper presented a method to support Policy Makers in identifying the mix of DG which best satisfies the needs of local load. The information collected through the proposed approach is supposed to be of direct interest, for example, in the definition of regional energy plans devoted to optimize the operation of distribution grids and minimize the requirements for new grid and generation infrastructures (transmission lines, transformers, conventional power plants, etc.).

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