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AlpStore project: a viable model for renewables exploitation in the Alps

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Abstract

Nowadays, the integration of intermittent and unpredictable Renewable Energy Sources (RESs) has led to new issues for the electrical system. The paper proposes a model, named Virtual Power System (VPS), which enables the management of generators and loads as a single (virtual) entity in order to achieve a "global" benefit, i.e. to improve the capability of the grid to host RESs. Moreover Energy Storage Systems (ESSs) could be integrated in the VPS in order to provide ancillary services: voltage regulation, primary frequency regulation and exchange profiles adjustment for a better RESs programmability. This work proposes a quantitative approach for ESSs design and integration in a VPS. Numerical results are reported with respect to an experimental application in the AlpStore project (Alpine Space Program 2007-2013).

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Keywords: Dispersed generation; virtual power system; energy storage system; ancillary services; voltage regulation; primary frequency regulation

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1. Introduction

Dispersed Generation (DG) is a new rising form of electricity generation that allows using renewable resources spread throughout the territory. Since now, DG has been integrated into the electrical system according to a "fit and forget" approach; so, since the current distribution network is designed as a passive system (i.e. not able to receive a high amount of generation), DG power injections can affect the quality of supply and the system stability. As DG penetration increases, it will become a technical and economic imperative that DG participates in the provision of

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ancillary services needed for an efficient, secure and reliable operation of the power system [1-2]. The ancillary services extension to DG connected at distribution level is essential also for a better integration of the DG itself and for increasing the capacity of the existing network to host Renewable Energy Sources (RESs): in the following this concept will be referred to as “Hosting Capacity (HC)” [3].

The approach proposed for the exploitation of the DG in supplying ancillary services is based on the Virtual Power System (VPS) concept: a set of resources, including DGs loads and (eventually) Energy Storage Systems (ESSs), distributed in a given area, are properly coordinated to provide network services for supporting the main electrical grid. To this purpose, the resources of the VPS have to be monitored and controlled in real time, as a virtual electric system.

In this paper, we discuss three main regulation functions (ancillary services) of the VPS. In the authors’ opinion, these functions are pivotal for the operation of electrical networks in the future scenario, characterized by a massive penetration of RESs:

- voltage regulation;
- primary frequency regulation;
- renewables exchange profile adjustment for a better RES programmability.

Concerning the voltage regulation, actually DG injections at distribution level alter the voltage profile along the feeders: in particular, it is no longer monotonous and over-voltages can occur (i.e. violations of EN 50160 prescriptions [4]). The VPS architecture can be exploited as a regulation resource for the enhancement of voltage quality; in particular, the reactive power can be modulated according to local measurements, i.e. using a local voltage control [5]. This is a simple, easy to set up, regulation structure, as no communication networks are required (no investment in network assets).

Concerning the frequency regulation, this service is required to control the system frequency and to guarantee the network stability. Nowadays, an ever-greater penetration of intermittent DG units, which are replacing traditional power plants, has caused a weakening of the system. Especially, this transformation entails a reduction of the total rotating inertia and a decreasing of the margin for the primary frequency reserve, i.e. lower capability to support the system in the case of power mismatch between load and generation [6].

Finally, the strong uncertainty characterizing RESs (typically owing to variation in weather conditions), for an effective integration of RESs in power systems, requires an improvement of the predictability of their power injections; such a predictability is quite important nowadays in order to allow an acceptable schedule of conventional generation connected to the main grid.

To achieve suitable network reliability and efficiency, technological solutions that involve Energy Storage Systems (ESSs) integrated in the VPS have to be considered. In this way, the VPSs can be used as regulation resources (capable of providing ancillary services) essential for the main grid (in particular, the aggregation of several resources in VPS results useful to limit the economic effort).

By adopting the model proposed, the new generation belonging to the VPS could be controlled in order to interact with the main grid ideally as a conventional power plant.

2. AlpStore project

In this study, a mathematical model of the ESS is created for simulating each of the above-mentioned regulation functions. The results of the analysis are then exploited to design an experimental prototype, which will be tested in the AlpStore research project framework [7]. Partners from seven countries of the Alpine area are taking part in this project, cooperating to create master plans for the deployment of storage and developing pilot tests to show the feasibility of mobile and stationary storage in the public infrastructure, business parks, enterprises and smart homes. From the Alpstore project, guidelines will be derived for planners and decision makers. The pilot applications range from RESs monitoring and forecasting, Demand Side Management, E-car charging process coordination, to the stationary storage prototype designed to provide ancillary services, which is the object of the present research work. In particular, Politecnico di Milano is carrying out the proposed test application in cooperation with Euroimpresa, a local cluster of SME (Small Medium Enterprise) sited North-West of Milan [8]. The pilot application is based on the monitoring and control of the electric energy needs of the TecnoCity (industrial area sited in Legnano, North-West of Milan, Fig. 1), coordinating, with regard to the functions presented in this paper, the operation of the ESS with the PV production (120 kW on the roof) and load consumption (the area is connected to the main grid by two MV/LV transformers that feed the lighting and thermal apparatus; moreover, each SME has its own meter devoted to energetic processes).

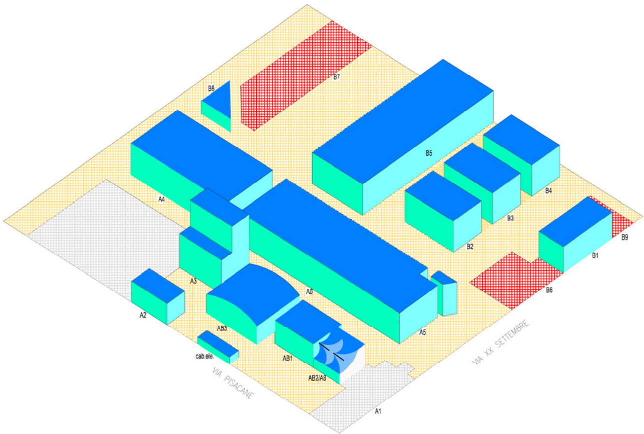

Fig. 1. Map of the TecnoCity area (blue buildings represent SME, grey dashed buildings are Euroimpresa officies, red dashed area are new buildings under construction; the total area covers more than 25000 m^2).

3. Voltage regulation

As described above, DG plants power injections can affect the voltage quality of the distribution system, increasing the voltage profile along the feeder with possible over-voltages.

According to the new standards in force in some European countries (CEI 0-21 [9] in Italy, VDE in Germany [10] and REE in Spain [11]), each DG plant connected to the LV system has to participate in the voltage regulation by the injection/withdrawal of reactive power. The regulation is based on local information: each generator operates in order to control the voltage profile at its Point of Common Coupling (PCC) with the main grid without any remote coordination with the other devices on the power system.

In this section, a study is carried out with the aim of analysing the local voltage regulation strategy of the DG, its impact on the voltage profile of the LV distribution network and the use of ESSs to support it: four different strategies (which summarize the various proposals contained in the current European standards) are taken into account (Fig. 2). The different control laws are classified according to the variables monitored at the DG's (and ESS's) PCC, as shown below.

- *Law A: $tg\phi = f(u)$*, control of the tangent of the angle ϕ as a function of the voltage at the PCC.
- *Law B: $q = f(u)$*, control of the reactive power as a function of the voltage at the PCC.
- *Law C: $tg\phi = f(p)$*, control of the tangent of the angle ϕ as a function of the real power injection.
- *Law D: $q = f(p)$*, control of the reactive power as a function of the real power injection.

The performances of the control laws are evaluated by computing the following indices: voltage profile enhancement, hosting capacity and real power losses of the network. The algorithm for the modulation of the reactive power according to the proposed control curves can be directly implemented in the inverter of the generators without involving the ESS. In fact, the production/injection of reactive power does not require a dedicated energy resource and much less a storage apparatus. Nevertheless, the ESS could satisfy this regulation, by means of the associated inverter, by only providing a reactive current, i.e. without requiring energy from the batteries.

In this scenario, the modulation of the reactive power has only a partial effectiveness on the voltage profile: this is particularly true in the LV distribution networks because of the resistive nature of the lines (high value of the R/X ratio). In these cases, over-voltages can persist despite the reactive power injection: it can be necessary to limit the energy production of the DG in order to avoid tripping of the interface protection and disconnection from the main system. In order to exploit the total RESs production, the ESS becomes essential to store the curtailed energy, which will otherwise be lost.

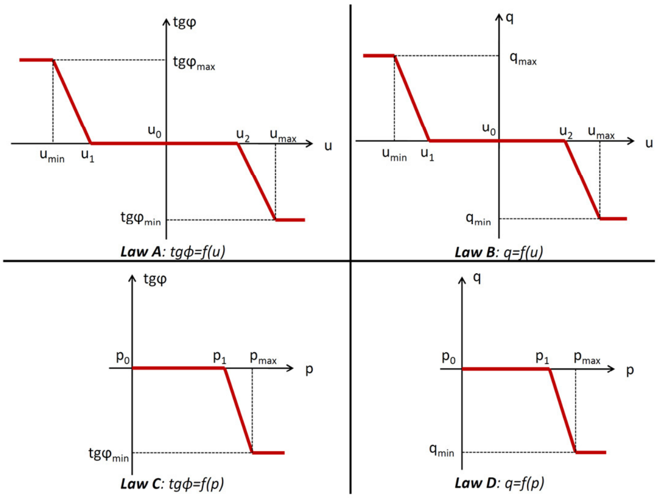

Fig. 2. Local control laws under analysis.

3.1. Numerical analysis

In order to evaluate the effectiveness of the proposed voltage control laws, some numerical analyses have been carried out exploiting a dynamic model built in MATLAB-Simulink/SimPowerSystem software. The case study network is the LV feeder reported in Fig. 3.

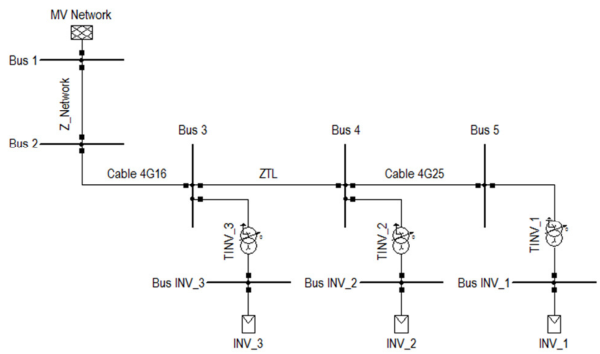

Fig. 3. Testing feeder.

Three PhotoVoltaic (PV) inverters were modelled: INV1 and INV2 (20 kW rated power) managed according to the four control laws, while INV3 (30 kW rated power) is used to represent a generic (variable) load.

$Z_{Network}$, $Z_{cable4G16}$ and Z_{TL} impedances are defined in order to obtain the equivalent series impedance $Z_{TOT} = 0.59 + j0.32\ \Omega$. This value is equal to the maximum feeder impedance value for 95% of LV Italian customers [12]. This impedance was chosen in order to simulate a weak network structure. Simulations are based on a one-year system operation: historical data are available for a PV power plant [13] (the curves are derived from meteorological data collected in the North of Italy); the power absorbed by each load is modulated according to the chronological curve of the LV user's consumption, which is estimated starting from data published in [14] and related to the average consumption of the secondary substations in the Italian distribution system. An overvoltage limit of +10%

of the rated voltage is considered (according to the EN 50160 prescriptions) in order to compute the Hosting Capacity index (HC in Table 1). The results show that, with a unitary power factor (DG operating condition previous to the CEI 0-21), the feeder can host only two power plants of 12.5 kW rated power, while the adoption of the reactive power control laws allows increasing the HC of the system up to 14.8 kW (for each generator).

Table 1. Feeder hosting capacity (P_{DG} of INV1 and INV2) with load INV3.

	HC [kW]	*ΔHC* [%]
cosϕ=1	12.5	-
Law A	14.5	+16.0%
Law B	14.8	+18.4%
Law C	13.3	+6.4%
Law D	13.3	+6.4%

Control laws A and B, in which the reactive power is computed as a function of the PCC voltage, are the most effective in terms of HC. On the contrary, laws C and D are less effective because the reactive production is linked to the real power injections.

In order to further increase the HC (i.e. higher integration of RES in the grid), the control strategy requires a limitation of the real power injected at the PCC. For this purpose, the study considers an ESS properly coordinated with the control law to achieve the real power limitation function without loss of PV production.

In Table 2 the results of a power injection equal to 20 kW (for both INV1 and INV2) are shown, thus exceeding the HC feeder. On the basis of this hypothesis, the performances of the four control laws are evaluated with regard to the following indices:

- h_{vio} [h]: annual hours of overvoltage violations.
- ΔE_{prod_PV} [kWh]: annual energy production of the DG unit w.r.t. the reference value of 44136 kWh/year, corresponding to the case of unitary power factor operation of the PV plants without any disconnection when over-voltages occur (the *Ideal scenario*).
- ΔE_{grid_loss} [kWh]: energy losses in the grid w.r.t. the reference value of 3428 kWh/year, which is computed in the *Ideal scenario*.

The simulations are carried out considering two possible operating conditions of the DG unit. In the first condition, INV1 and INV2 are disconnected from the grid by the Interface Protection System (IPS) in the case of over-voltages at the PCC (as required by Italian standard CEI 0-21), with consequent lack of production of the generator. In the second condition, real power injections are limited by steps of 10% of the rated power in order to avoid over-voltages. The results of Table 2 show that control Law B (included in the CEI 0-21) is the most effective in terms of improvement of the h_{vio} index (decreasing by 77.1% compared to the cosφ=1 condition) and DG production curtailment to reduce the over-voltages (0.08% of energy curtailment w.r.t. the *Ideal scenario*). Anyway, Law B allows a higher injection of energy and a higher energy losses increase (+9.5%).

The results show that the storage could be effective for this application: in fact, it is necessary to store only a small percentage of DG energy production (ΔE_{prod_PV} in Table 2). In particular, the analysis shows that in the worst case (i.e. ESS sizing made according to the peak power of the PV plant), the ESS requires a rated power just a little bit lower than the difference between the DG size and the HC computed in the connection bus (usually in a range between 96.6% and 98% of this difference). On the contrary, the energy capability varies according to the generator size: in the case where the size of the generator is almost equal to the HC, the capacity required to the ESS is small: about equal to one equivalent hour of operation. Only if the size of the generator is much greater than the grid HC (e.g., 150%) the ESS capacity rises up to 5-6 equivalent hours.

For the implementation in the AlpStore project, the ESS will provide only reactive power regulation in order that the grid can support these generators without problems (actually HC is greater than the already-in-place PV plant nominal power: 120 kW). Nevertheless, ESS could be useful in order to support new PV generators that could be installed in the area.

Table 2. Simulation results for P_{DG} = *20 kW*

	IPS tripping of DG unit			DG Power Limitation	
	h_{vio} [h]	ΔE_{prod_PV} [KWh]	ΔE_{loss_rete} [kWh]	ΔE_{prod_PV} [KWh]	ΔE_{loss_rete} [kWh]
cosϕ=1	575	-3226 (-7.31%)	-463 (-13.5%)	-318 (-0.72%)	-48 (-1.39%)
Law A	198 (-65.6%)	-1046 (-2.37%)	-180 (-5.2%)	-88 (-0.20%)	+149 (+4.34%)
Law B	132 (-77.1%)	-504 (-1.14%)	+136 (+3.9%)	-35 (-0.08%)	+326 (+9.51%)
Law C	474 (-17.6%)	-2665 (-6.04%)	-424 (-12.4%)	-225 (-0.51%)	-21 (-0.61%)
Law D	425 (-26.1%)	-2224 (-5.54%)	-381 (-11.1%)	-269 (-0.61%)	-32 (-0.93%)

4. Primary frequency regulation

As already introduced, in a VPS approach, the energy resources could be coordinated in order to modulate the real power injections (frequency regulation) and to improve the system operation in case of significant power imbalances. The Energy Storage System (ESS) integrated with DG can ensure the margin of power required for the service. A dynamic model of a PV System coupled with an ESS was developed with the aim of simulating its contribution to reestablish the power balance in the network. The new apparatus, in the case of frequency deviations from the nominal value Δf, modulates the power injections ΔP following a droop function (according to the ENTSO-E network code, Fig. 4).

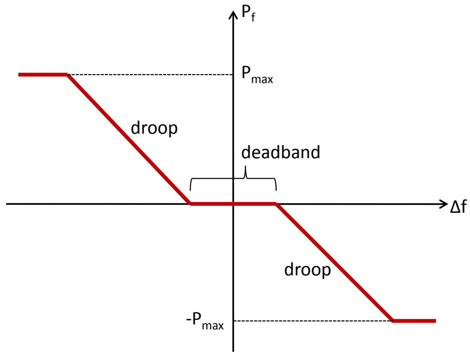

Fig. 4. ENTSO-E network code - Real power modulation according to frequency deviation: Droop control.

Frequency curve parameters used for the simulations were set in compliance with the ENTSO-E prescriptions:

- Dead band: 20 mHz.
- Droop control: 2%.
- Maximum power capability P_{max} (injection/withdrawal): 3% of the rated power.
- Minimum time to deliver the maximum capability: 15 minutes.

A simplified network model was built in the PowerFactory DIgSILENT software (Fig. 5). The network model integrates a PV power plant with an ESS in a DC-coupled system. The system is connected to the AC network (External Grid, modelled as an ideal voltage source) through a grid following inverter (INVERTER). The PV system injects its optimal power (MPPT is achieved), whereas the DC/DC converter of the ESS (i.e. ESS Converter of Fig. 5) controls the charge/discharge of the ESS in order to provide the energy required for the frequency control.

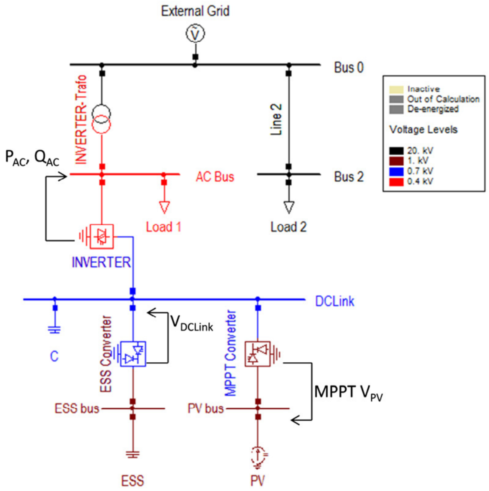

Fig. 5. Network scheme of the PV system integrated with an ESS in a DC-coupled system.

The parameters of the control system are tuned in order to provide the entire regulation band and to fulfil the ENTSO-E prescriptions. The behaviour of the ESS is analysed by evaluating its response to a real one-day frequency oscillation of the electrical system (the frequency oscillations are real measured data related to the electric European system [15], **Errore. L'origine riferimento non è stata trovata.**). The real power delivered by the ESS in compliance with the droop control is shown in **Errore. L'origine riferimento non è stata trovata.**. The number of equivalent cycles of complete charge and discharge, N_{ch} and N_{dis} respectively, required for this application in one day are computed. If a regulation band of 3% of the rated power is supposed (P_{max} in Fig. 4), the storage has to provide about four complete charge and discharge cycles per day ($N_{ch} = 3.964$, $N_{dis} = 3.869$); therefore, the primary frequency regulation provided by the VPS requires a significant use of the storage apparatus. In fact, about 1460 complete charge and discharge cycles per year are required (quite a lot when compared to the ESS life cycles of commercial apparatus, ranging from 3000 to 5000).

Concerning the AlpStore project, supposing to apply a regulation band equal to ±3% of the PV power plant nominal power (120 kW, already in place in the TecnoCity area), adopting the proposed approach an ESS sized at 3.6 kW for, at least, 15 minutes (about 0.9 kWh), is needed.

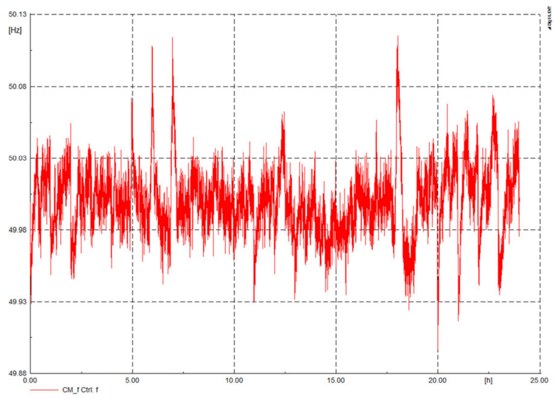

Fig. 6. One day frequency oscillations.

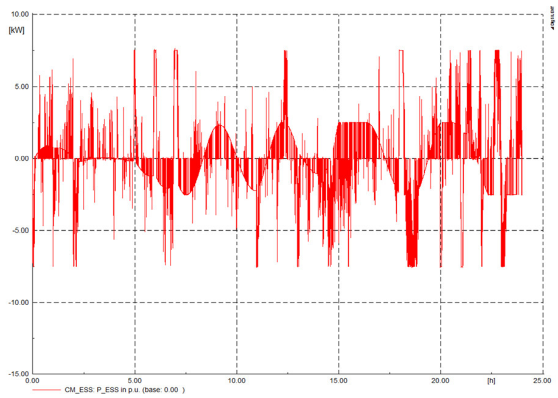

Fig. 7. One day power exchanged by the ESS.

5. Increasing of the energy profiles forecast accuracy

The RES fluctuations are the main cause of the unpredictability of the energy flow in the grid, reducing the system efficiency and reliability. In perspective, the improvement of the forecasting accuracy of the load/generation power withdrawals/injections is one of the most promising services that can be provided by the VPS: it should adjust the power profiles in order to respect a specific energy exchange program. For this purpose, the ESSs have to be integrated in the VPS and coordinated with the operation of the load and generation by using prediction algorithms specific to the user category and to the primary source under analysis. To this end, the systematic collection of information is essential in order to build a historical archive of users behaviour, allowing a better estimation of their future energy profiles.

In this section, a numerical analysis is performed to design an ESS able to adjust the exchange profile of the VPS, making it predictable/programmable. The aim of the approach is to define functional requirements (power and energy) of an ESS to maintain the prediction error (imbalances) within a given target, regardless of the specific storage technology. The study is carried out on the basis of the production data of a real PV plant ($P_n = 96.33\ kWp$). With the purpose of estimating the PV hourly production, the weather forecasts made available by a dedicated web service for the installation site of the power plant (located in the Northern Italy) were acquired and processed. The analysis was conducted over a time period between September 2012 and April 2013. It is assumed that the prediction of the exchange profiles is required one day in advance, admitting a tolerance for the hourly forecast of 10% of the hourly program. The analysis is divided into the following phases:

- starting from the data of the production and irradiation of the PV plant, the mathematical model that best approximates the power plant operation is defined through a linear regression algorithm;
- the weather forecasts acquired by the service provider (24 hours in advance) are applied in input to the mathematical model, estimating the hourly production of the PV plant;
- the current production measured at the terminals of the PV plant is compared with the estimated one, determining the error affecting the PV production forecasts;
- the prediction error is corrected by means of an ESS, iterating the analysis for different storage sizes (power, energy) and exploiting the residual imbalance as performance index.

A first order model is adopted to model the PV plant; it linearly correlates the power produced by the PV plant and the irradiation incident on the PV panels:

$$P_{eff} = \frac{P_n}{I_{STC}} \cdot I_{eff} \tag{1}$$

- P_{eff} is the current hourly production measured at the terminals of the PV plant [W];
- I_{eff} is the hourly irradiance applied to the PV panels [W/m^2];
- I_{STC} is the hourly irradiance in STC conditions [W/m^2];
- P_n is the rated power of the PV plant [W].

Eq. (1) provides a first indication of the correlation between the PV production and the solar irradiance, but it does not take into account several time dependent factors (such as, wearing and maintenance status of PV panels, seasonality, temperature, humidity, etc.). To take into account these factors, the proportional relationship between solar irradiation and hourly production is determined through a linear regression algorithm: starting from the historical data collected on a specified time horizon (e.g. up to one week in advance), the algorithm evaluates the correlation coefficient of the PV model. By this elaboration, a mathematical model varying in time with hourly resolution is obtained.

Experimental results highlighted that the number of time samples (*hs*) suitable to instruct the linear regression algorithm is 100 (considering only daytime hours). By increasing the number of samples the parameter of the model will be more stable over time, because it is less sensitive to accidental phenomena (e.g., failures); on the contrary, it will be unable to properly reflect changes to boundary conditions.

Then, the correlation coefficient (equal to 0.079) is applied to the radiation forecast provided by the web service and, finally, the effectiveness of the ESS in reducing the amount of imbalances is investigated. The analysis is carried out varying the ESS size, evaluating in each simulation the percentage of energy production affected by imbalances on the observation period considered. The results are reported in Table 3: the columns show the ESS power in percentage w.r.t. the size of PV power plant, while the rows show the ESS capacity in percentage w.r.t. an equivalent hour of operation of the PV plant. Imbalances are reported as percentage of the annual PV production. From Table 3 one can observe that, for example, an ESS with a capacity equal to 10% of an equivalent hour of operation of the PV plant and a power equal to 10% of the generator size (i.e. with a capacity of 9.6 kWh and a rated power of 9.6 kW, the size of the PV plant being equal to 96.33 kW) is able to reduce the yearly imbalances to about 8.4% of the total yearly production (compared to 13.4% of the solution without ESS). Moreover, at the increasing of the ESS size, in power and energy, there is a further reduction of the annual production subject to imbalance fees. In particular, a much higher benefit is given by increasing the ESS energy than the ESS power (as shown in Table 3).

Regarding the application in the AlpStore project, assuming as target for the experimentation to limit the imbalances at 10% of the DG yearly production, an ESS with 12 kW/12 kWh is necessary.

Table 3. Percentage of production subject to imbalances, according to the ESS power and capacity (power in % w.r.t. the power of the PV plant; energy in % w.r.t. an equivalent hour of operation of the PV plant).

		Power				
		10%	20%	30%	40%	50%
Energy	10%	8.46	8.46	8.46	8.46	8.46
	20%	6.22	6.21	6.21	6.21	6.21
	30%	4.91	4.88	4.88	4.88	4.88
	40%	3.98	3.91	3.91	3.91	3.91
	50%	3.29	3.18	3.18	3.18	3.18
	60%	2.79	2.59	2.59	2.59	2.59
	70%	2.42	2.07	2.07	2.07	2.07
	80%	2.16	1.66	1.66	1.66	1.66
	90%	1.92	1.37	1.37	1.37	1.37
	100%	1.73	1.10	1.10	1.10	1.10

6. Conclusion

At present, DG is causing many technical problems in the existing networks, owing to the fact that the conventional power system was not designed to integrate generation from RESs connected to the distribution system. However, DG units can also provide different ancillary services for the network operation, meaning that DG can be transformed from being a part of the problem into a part of the solution. In this framework, VPSs and ESSs could be a useful resource to support the integration of RESs in the networks, making DG injections more predictable and controllable and providing the ancillary services necessary to the system to effectively manage RESs. The paper exploits the VPS concept, which considers DG and loads integrated with ESSs, to provide ancillary services to the electrical system, focusing on the sizing required to the ESS in each of the applications under consideration. The proposed approach aims at exploiting ancillary resources spread along the network instead of using centralized resources.

In order to size the ESS properly, it is necessary to consider the power and energy requirements for each function evaluated separately, as listed below.

- Voltage regulation: in the worst case (ESS sizing made according to the peak power of the PV plant), the storage power must be equal to the difference between the DG size and the maximum DG injections that can be accepted by the grid without violations of the voltage limits, while the ESS capacity can be usually 1-2 equivalent hours of operation of the DG.
- Primary frequency regulation: the ESS power is equal to 3% of the size of the generator, while the ESS energy is equal to 0.25 equivalent hours.

- Exchange profiles adjustment for forecasting purposes: to achieve imbalances lower than 10% of the DG yearly production, the ESS power has to be equal to 10% of the generator size, while the ESS capacity must be equal to 10% of an equivalent hour of the DG.

This study provided useful indications for the implementation of the experimental application on field of the AlpStore project, sited in the TecnoCity area in Legnano (North-West of Milan city).

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