STORAGE APPLICATION FOR ANCILLARY SERVICE SUPPORT TO THE MAIN GRID

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

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

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

Gabriele MONFREDINI
Politecnico di Milano – Italy
gabriele.monfredini@polimi.it

Stefano NASSUATO
FIAMM Energy Storage
stefano.nassuato@fiamm.com

Claudio ROSATI
MCM Energy Lab – Italy
c.rosati@mcmenergylab.com

Gabriele MARCHEGIANI
ELVI group – Italy
gabriele.marchegiani@elvi-italia.com

ABSTRACT

Nowadays, the high penetration of Dispersed Generation (DG) introduces new issues in the stability and safety of the electrical system due to the intermittent and not deterministic behavior of Renewable Energy Sources (RESs). The paper proposes an extension of the ancillary services, usually provided only by conventional power plants, to the DG units, in order to improve the power quality of electrical networks and to enhance their capability to host RESs through the integration of Energy Storage Systems (ESSs). Three main services have been analyzed: primary voltage regulation, primary frequency regulation and exchange profiles adjustment to increase RESs programmability. First, a numerical analysis of the three services has been carried out by exploiting numerical models, and then an experimental application is presented.

INTRODUCTION

Dispersed Generation (DG) is a new rising form of generation which allows using Renewable Energy Sources (RESs) spread throughout the territory. As DG penetration increases, it will become a technical and economic imperative that DG participates in the provision of ancillary services needed for an efficient, secure and reliable operation of the power system [1][2].
For this purpose, new technological solutions, that could involve Energy Storage Systems (ESSs), have to be considered in order to compensate the intermittency and unpredictability of RESs and guarantying a suitable power margin for the provision of ancillary services.
The paper presents the results of PRESTO (Primary REgulation of STOrage) project, a research collaboration among the Department of Energy of Politecnico di Milano, MCM Energy Lab and ELVI, with the technical support of FIAMM ESS. The purpose of PRESTO is to develop new regulation features for ESSs to provide ancillary services to the main grid. Three main services are analyzed: voltage regulation, primary frequency regulation and improvement of renewables exchange profiles programmability; in the following a short motivation is reported.
The provision of the voltage regulation service by DG units covers a particular interest because of the effects of DG injections on the voltage profile along MV/LV feeders: in fact, when the electricity production from RESs increases, the voltage profile could be no longer monotonous and over-voltages at the DG's Point of Common Coupling (PCC) could occur (i.e. violation of EN 50160 prescriptions [4]). ESSs can be exploited as regulation resource for the enhancement of the voltage quality; in particular, the reactive power can be modulated according to local measurements at the PCC, i.e. exploiting a local voltage control.
The second ESS service evaluated is the primary frequency regulation service. It is devoted to control the system frequency and to guarantee network stability. Nowadays, an ever-greater penetration of intermittent DG units, replacing traditional power plants, causes a weakening of the system, especially a reduction of the total rotating inertia and a decreasing of the margin for the primary frequency reserve [3]. The ESS control developed has the purpose to provide frequency regulation with performance similar to that of conventional power plants.
Finally, the RES profile production is usually subject to strong uncertainty due to the variation in weather conditions. An improvement in the prediction of the energy production, also by the support of ESSs, is required to determine the operation condition of the system in the short time and to schedule consequently the conventional generators on the grid.
In the paper numerical analyses are carried out in order to test each of the ancillary services above described. In particular, the behavior of the ESS is evaluated for each application and a suitable storage sizing is proposed. Finally, the results obtained in the numerical analyses have been exploited to design an experimental prototype, which is used in the PRESTO project to validate the results obtained in the numerical simulations and to test the proposed strategies in a real test facility.

VOLTAGE REGULATION

According to new standards in force in some European countries (CEI 0-21 [5][6] in Italy, VDE [7] in Germany and REE [8] in Spain), each DG plant connected to the LV system has to participate in the voltage regulation by the injection/absorption of reactive power. In the proposed approach each generator operates locally without any coordination with the other devices on the power system, in order to obtain a voltage profile without violations.
In this section, a numerical study is carried out with the aim to analyze the local voltage regulation strategy and its impact on the voltage profile of the LV distribution network: four different strategies are taken into account (Fig. 1). The different control laws are classified according to the variables monitored at the DG PCC, as shown below:

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

The algorithm of modulation of the reactive power according to the proposed control curves can be directly implemented in the inverter of the generators (e.g. photovoltaic power plants) without involving the ESS. In fact, the production/injection of reactive power doesn't require a dedicated energy resource and much less a storage apparatus. Nevertheless, the ESS could provide, by means of the associated inverter, this service for already in place power plants (i.e. ESS could be an effective retrofit option).

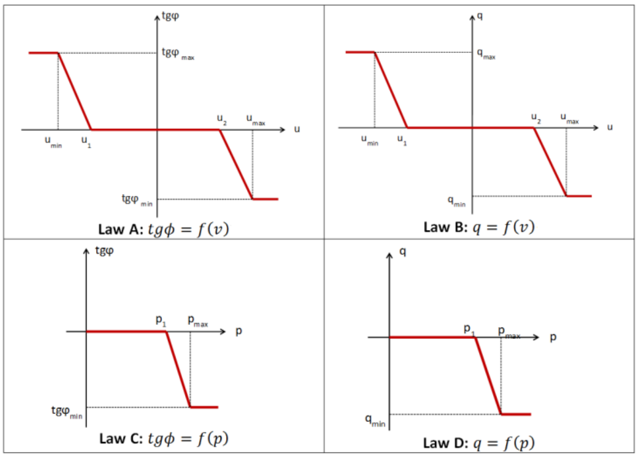

Fig. 1: Control laws analyzed.

Numerical analysis

In order to evaluate the effectiveness of the proposed control laws, some numerical analyses have been carried out exploiting a dynamic model based on MATLAB-Simulink/SimPowerSystem software. The case study network is the LV feeder reported in Fig. 2.
Three Photovoltaic (PV) inverters were modeled: INV1 and INV2 (20 kW rated power) managed according to the four control laws, while INV3 (30 kW rated power) represents a generic (variable) load.
$Z_{Network}$, $Z_{cable\ 4G16}$ 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 the 95% of Italian LV customers [9]. The performance of the control laws are evaluated by computing the HC index (reported in Table I). Simulations are based on a one-year system operation: historical data are available for a PV generation profile [10] (the curves are derived from meteorological data in an area of the North of Italy). An overvoltage limit of +10% of the rated voltage is considered (according to the EN 50160 prescriptions). The results show that, for a unitary power factor operation condition (DG operation previous to the CEI 0-21), the feeder can host only two power plants of 12.5 kW, while the adoption of the reactive power control laws allows increasing the HC of the system up to 18.4%.

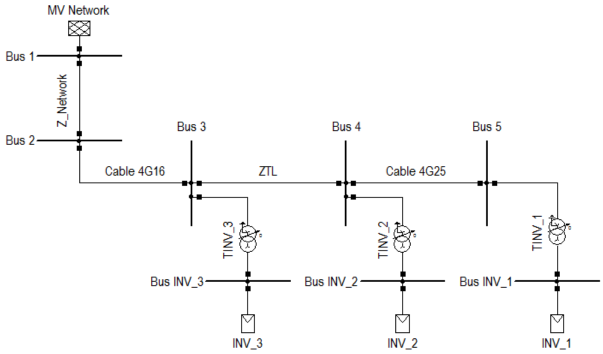

Fig. 2: Testing LV grid.

TABLE I: 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%

TABLE II: Local Voltage Control coordination with an ESS - performances evaluation

Local voltage control law	Hour in a year with voltage violation [h]	ESS size [kWh]
cosϕ=1	575	
Legge A	198 (-65.6%)	88
Legge B	132 (-77.1%)	35
Legge C	474 (-17.6%)	225
Legge D	425 (-26.1%)	269

The results show also that the control laws A and B are the most effective in terms of HC improvement. Anyway, the modulation of the reactive power has only a partial effectiveness on the voltage profile due to the resistive nature of LV distribution feeders (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 production of the DG, and the ESS becomes essential to store the curtailed energy which will otherwise be lost. For this purpose, the study considers an ESS properly coordinated with the control law implemented on the PV inverter to achieve the real power limitation function. The new case study considers a power injection equal to 20 kW (for both INV1 and INV2), thus exceeding the feeder's HC. By operating at unitary power factor, overvoltage violations may occur in 575 hours in a year: in these cases, the generator would be disconnected by its own interface protection system. If a portion of the real power is stored in the ESS instead of to be injected in the grid, the voltage violations can be easily extinguished. The simulations demonstrate that, in order to avoid voltage violations, 318 kWh (corresponding to 0.72% of the theoretical energy availability) have to be stored in the ESS in a year. The combination of this strategy and the reactive power modulation can reduce the amount of energy involved by the ESS up to 35 kWh if Law B is used. Actually, ESS coupled with a local voltage control results to be a good in order to manage overvoltage problems without generation curtailment.

PRIMARY FREQUENCY REGULATION

The ESS can ensure the margin of power required to support the frequency regulation capability and to improve the system operation in case of significant power mismatch between load and generation. A dynamic model of a PV system (PV in Fig. 3) coupled with an ESS was developed with the aim to simulate its contribution to the reestablishment of the power balance on the network. The new apparatus, in the case of frequency deviations from the nominal value, modulates the power injections following a droop function (according to the grid code proposed by ENTSO-E, Fig. 4).

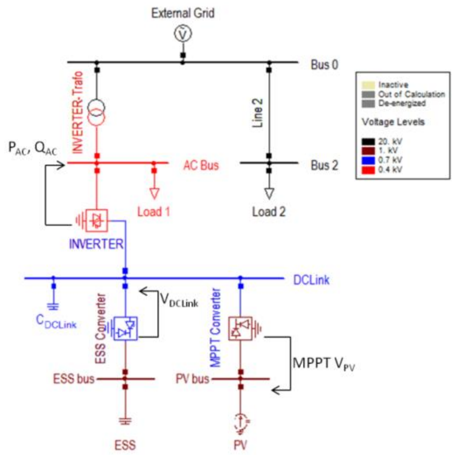

Fig. 3: Network scheme of the PV system integrated with an ESS in a DC-coupled system.

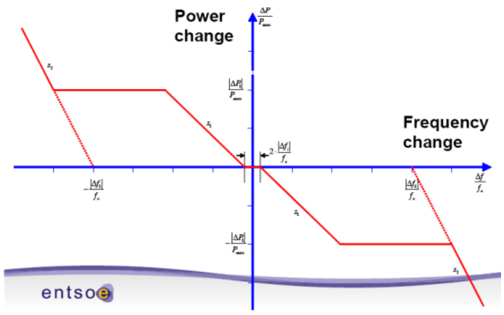

Fig. 4: Real power modulation according to frequency deviation: Droop control [3].

A simplified network model was built in the PowerFactory DIgSILENT software (Fig. 3).

The network model integrates a PV power plant with an ESS in a DC-coupled system. The system is connected to an AC network (External Grid, modeled 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. 3) controls the charge/discharge of the ESS in order to provide the energy required for the frequency control.

The parameters of the control system are tuned in order to provide the entire regulation band and to fulfill the ENTSO-E prescriptions.

The behavior of the ESS is analyzed by evaluating its response to a real one-day frequency oscillation of the electrical system (the frequency oscillations are a real measured data related to the electric European system [11]). The profile of the real power delivered by the ESS in compliance with the droop control is shown in Fig. 5. In the case of droop equal to 2% and deadband equal to 20 mHz, the number of equivalent cycles of complete charge and discharge (respectively, N_{ch} and N_{dis}) required for this application in one day are computed. If a regulation band of 3% of the rated power is supposed, the storage has to provide about six complete charge and discharge cycles per day; therefore, the primary frequency regulation requires a significant use of the apparatus.

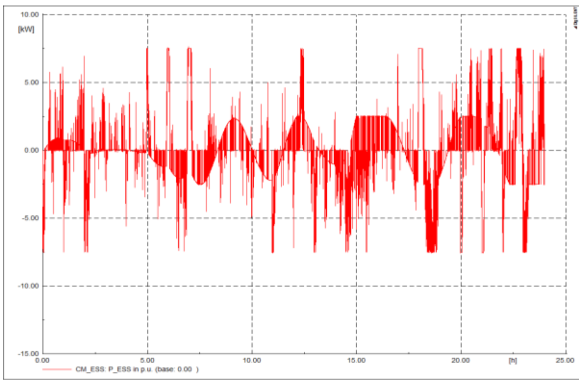

Fig. 5: One day power exchanged by the ESS

In Table III the number of complete charge and discharge cycles in one day are computed with different operation settings of the droop control. These two indices are directly connected to the energy adopted for the frequency regulation. On the basis of the results it can be stated that the parameters deadband and droop of the curve have a significant impact on the energy modulated by the ESS and on the choice of a proper size for this application.

TABLE III: Complete charge and discharge cycles computed from the P_{ESS} for each simulation setting.

Deadband [mHz]	Droop [%]	Nch	Ndis
20	2	5.645	5.549
10	2	7.484	7.132
40	2	2.818	3.056
20	1	6.711	6.530
20	4	3.995	3.873

INCREASING OF THE ENERGY PROFILES FORECASTING ACCURACY

RESs fluctuations and unpredictability reduce the programmability of the DG power production: i.e., the energy flows on the power system cannot be forecasted with an adequate accuracy, and then suitable security margins must be taken in dispatching conventional generators. In the perspective, the ESS can offer a promising improvement of the forecasting accuracy of DG power injections (and load withdrawals). The power modulation of the ESS can be exploited to adjust the power profiles of the DG in order to respect a specific production program.

In this section, a numerical analysis is performed to design an ESS that, coupled with a RES power plant, adjusts its exchange profiles so as to obtain an easily predictable/programmable DG units. 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 (Pn = 96.33 kWp). With the purpose to estimate 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 North of Italy) have been acquired and processed. The analysis has been 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 in 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].

The Eq. (1) provides a first indication of the correlation between the PV production and the solar irradiance, but it doesn't 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. So, 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).

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 IV: 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.

TABLE IV: Energy production [%] subject to imbalances, w.r.t. 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

Imbalances are reported as percentage of the annual PV production. From Table IV it is possible to 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, being the size of the PV plant 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 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.

PRESTO PROJECT

In addition to the numerical analyses, each ancillary service has been tested on field. The three proposed applications of the ESS have been implemented in the PRESTO project. The test facility is located in Legnano city (North-West of Milan). In particular the ESS apparatus has been connected in an industrial area, named TecnoCity, already supplied by a 120 kW PV power plant. Moreover, a monitoring architecture has been deployed in order to collect information from the ESS, from the PV power plant and from the MV/LV transformer that feeds the area [12]. The PRESTO architecture in the test facility (Fig. 6) is based on a 23 kWh $NaNiCl_2$ storage apparatus connected to the 400 V grid of the test facility through a 10 kW inverter. A proper software algorithm has been developed and implemented in a PLC which coordinates both the inverter logic and the ESS. Such an experimental campaign (three month application), devoted to collect information to validate the numerical model proposed in this paper, will be completed by the end of May 2014.

CONCLUSION

Today, RESs are causing many technical problems on the power systems due to the fact that they are connected to electrical networks (which have been designed as passive systems) with a fit and forget approach, and they are scarcely programmable generation resources. However, DG units can also provide different ancillary services for the network operator. ESS technologies can play an important role in this scenario, because they can be properly managed to support the integration of RESs in the networks, making DG injections more predictable and controllable. The paper analyzes with a numerical approach the use of ESSs according to the three proposed ancillary services. Several study cases are simulated with the aim to find a proper storage size which allows to compensate the intermittent behavior of the DGs and to achieve the power quality requirements of the system. After this theoretical study, a prototype has been installed in a test facility to demonstrate the feasibility of the ancillary service algorithms proposed and to validate the numerical results obtained in the simulations.

REFERENCES

[1] M. Delfanti, D. Falabretti, M. Merlo, 2013, "Dispersed generation impact on distribution network losses", *Electric Power Systems Research*, vol.97, 10–18.

[2] M. Delfanti, M. Merlo, G. Monfredini, V. Olivieri, M. Pozzi, A. Silvestri, 2010, "Hosting dispersed generation on italian MV networks: towards smart grid", *ICHQP 2010 14th international conference on Harmonics And Quality Of Power*, paper 1404.

[3] ENTSO-E. Network Code for Requirements for Grid Connection applicable to all Generators, Available online: https://www.entsoe.eu. June, 2012.

[4] European standard EN 50160, *Voltage characteristics of electrical supplied by public distribution systems*, CENELEC TC 8X, 2008.www.terna.it.

[5] G. Monfredini, M. Delfanti, M. Merlo, A. Cerretti, E. De Berardinis, 2011, "Voltage regulation issues for smart grid", *Cigrè International Symposium*.

[6] Italian Electrical Committee (CEI), 2012, *Technical standard CEI 0-21, Reference technical rules for the connection of active and passive users to the LV electrical Utilities, in Italian*, Milan.

[7] BDEW, 2008. Generating plants connected to the medium-voltage network, guideline for generating plants connection to and parallel operation with the medium-voltage network.

[8] REE, 2009. Spanish Grid Code. Available: http://www.ree.es/ingles/home.asp.

[9] EURELECTRIC, 2002, *Power quality in European electricity supply networks – 1° edition, Network of Experts for Standardization*, Ref: 2002-2700-0005.

[10] D. Falabretti M. Merlo L. Megalini A. Capone, M. Delfanti, 2011, "PV production forecast for an effective VPP exploitation", *Cigrè International Symposium 2011*, pages 1–7.

[11] Netzfrequenzmessung, 2011. *Beispieltag der Netzfrequenzmessung mit Minuten- und Sekundenwerten*, 8 March 2011. Available Online: www.netzfrequenzmessung.de.

[12] www.tecnocity.it, 2014.

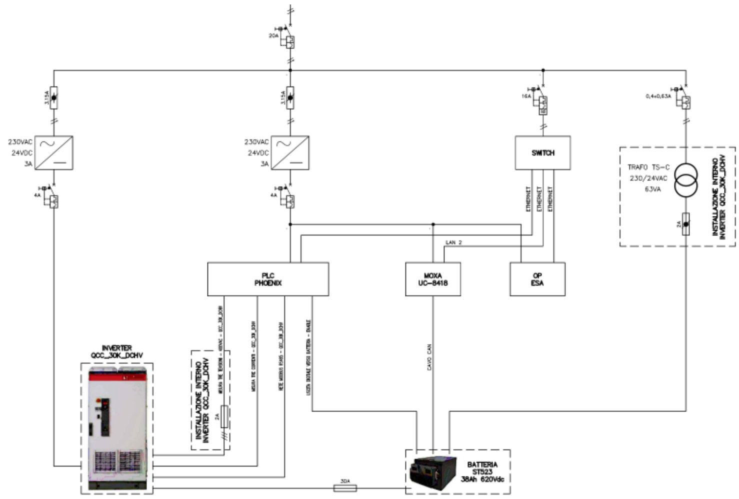

Fig. 6: Network scheme of the Inverter and ESS in the test facility.