Dispersed generation to provide ancillary services: AlpStore project

M. Delfanti*, L. Frosio**, M. Merlo*, G. Monfredini*, L. Pandolfi***, C. Rosati**, D. Rosati**
*Politecnico di Milano, Piazza Leonardo da Vinci 32, Milano, (*Italy*)
**MCM Energy Lab s.r.l., Via Giovanni Durando 38/A, Milano (*Italy*)
*** Euroimpresa, Via Pisacane, 46 20025 - Legnano (MI)

Abstract – **In the future, electrical systems should be able to integrate all users at the same time and guarantee power quality, stability and safety over time. The integration of renewable energy sources leads to new issues involving the intermittence of this generation typology. A high penetration of intermittent power plants will reduce the capability of the system to overcome critical events (e.g. frequency oscillations and voltage profile perturbation). This work presents new regulation schemes/functions developed in the AlpStore project framework, devoted to managing dispersed generation in order to provide ancillary services to the main grid. The work developed can be split into two main items: reactive injection regulation and frequency control regulation. The first regulation is devoted to increasing the Hosting Capacity of the distribution grid (i.e. it results to be a local control), whereas the latter aims to guarantee the energy balance of the national electric grid (i.e. it could be classified as a grid control).**

Index Terms – **Dispersed generation, renewable generator, smart grid, ancillary services, active power control, reactive power control, storage system.**

I. Nomenclature

DG: Distributed Generation
PV: PhotoVoltaic
P: real power
Q: reactive power
PCC: Point of Common Coupling
LV: Low Voltage
IPS: Interface Protection System
SS: Secondary Substation

II. Introduction

Dispersed Generation (DG) is defined as a set of generation plants with rated power up to 10 MW, connected to medium voltage (MV) and low voltage (LV) distribution networks. By this new form of generation it is possible to use renewable resources, which are spread throughout the territory, reducing the use of fossil fuels. DG is being integrated into the electrical system according to a "fit and forget" approach; since the current distribution network is designed as a passive systems (i.e. not able to receive a high amount of generated power) high DG power injections may 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 ancillary services needed for a secure and reliable operation of the power system [1][2]. This is important for the simple reason that if DG only displaces the energy produced by central generation but not the associated flexibility and capacity, the overall cost of operating the entire system will rise. Moreover the DG impact on network losses [3][4], and on network congestions [5], have to be carefully evaluated .

Increased penetration of DG will increase DSO options regarding network operation and planning, which could lead to lower overall costs. Consequently, such services will represent incremental revenue opportunities even for DG.

The distribution system operator will become responsible for the distribution network management and the maximization of local sources dispersed in the network. In the absence of a clear policy and associated regulatory instruments on the treatment of DG, it is very unlikely that this type of generation will thrive.

The new scenario implies new rules for the active users connected to the distribution network. Until now, DG power plants have not offered any ancillary service for the network operation. Nowadays, demand is growing from large utilities (DSO and TSO) to exploit DG as a service for the system. In this way generators connected along the distribution system are a resource useful to improve the stability, safety and power quality of the electric grid. They are a regulation resource dispersed along the feeders and potentially they can offer a network control in remotely points of the distribution network normally not controlled. Furthermore, the ancillary services extension to DG connected to the distribution level is essential also for a better integration of the DG itself and for an increasing of the hosting capacity of existing networks. These services involve both the transmission and distribution system management.

The most important system services offered by DG units can be divided into two categories: a) reactive power modulation service, b) real power modulation service.

It is important to point out the difference between these control services in term of impact on the system.

DG injections at distribution level alter the voltage profile along the feeders: in particular it is no longer monotonous and over-voltages at the DG Point of Common Coupling (PCC) can occur (i.e. violation of EN

50160 prescriptions [4]). The reactive power modulation services mainly allow the voltage of the system to be controlled. In particular, DG reactive power could be modulated according to local measurements at the DG PCC, i.e. exploiting anew local voltage control [2][3][7]: This control strategy has been considered also in the Italian rules for the connection of active users to the distribution system. This is a simple, easy to set up, regulation structure, as no communication networks are required (no investment in network assets).

On the other hand, the real power modulation service is required by the TSO to control the system frequency and guarantee network stability. 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, i.e. with lower capability to support the system in case of frequency oscillations. Because of this, the margin of power available for the frequency control provided by traditional plants could become insufficient to face a sudden power imbalance (e.g. owing to loss of generation or load increasing).

A real event happened during the islanding operation (i.e. an operation of the network disconnected from the rest of the electrical system) of the transmission network of the Sicily region on 18 May 2011 [5]. Owing to the weakly meshed network topology and to the strong penetration of renewable power plants, damage to one traditional power plant caused a strong frequency decreasing and loss of DG and 200 MW of load shedding were necessary in order to restore power balance. Actually in Italy the grid has to face classical congestion problems [6][8] and new criticisms related to frequency oscillation not effectively supported by renewable generators [9].

In order to achieve suitable network reliability, technological solutions that involve Energy Storage Solutions (ESS) have to be considered. In this way, renewable energy sources can be exploited to provide ancillary services to the main grid. The purpose of the work is to equip the DG with an ESS in order to provide a suitable margin for the frequency regulation service as much as a traditional power plant. Therefore, participation in primary frequency regulation is extended also to renewable power plants.

III. REACTIVE POWER MODULATION SERVICE

Electricity distribution networks are designed to feed passive loads. The power injected by Distributed Generation (DG), at both medium and low voltage distribution networks, introduces new issues of network management. DG plants affect the voltage quality of the distribution system: in particular, the voltage profile along the feeder is no longer monotonous and over-voltages can occur at the Point of Common Coupling (PCC) of the DG units.

According to the new Italian standard CEI 0-21 [10], each DG plant connected to the LV system has to participate in voltage regulation by the injection/absorption of reactive power.

Two different control strategies can be adopted. In the first strategy, named Local Control, a) each generator operates without any coordination with other devices; according to the second strategy, named Global Control, b) all regulating resources are coordinated and remotely controlled in order to obtain an optimal voltage profile.

Both Local Control and the Global Control are mentioned in the CEI 0-21 standard. In particular, concerning the voltage regulation (i.e. the reactive power modulation) two particular local control laws are considered: $\cos\varphi = f(P)$ and $Q = f(V)$.

Afterwards, a study is carried out with the aim to analyze the impact of four different strategies (which summarize the various proposals contained in the current European standards, including those introduced in CEI 0-21) on the voltage profile of the LV distribution network. According to this control scheme, each DG plant is exploited as a reactive power resource in order to mitigate the over-voltages along the feeder.

The performance of the control laws are compared to each other in terms of voltage profile enhancement, hosting capacity improvement and real power losses in the network.

The different control laws are classified according to the variables monitored at the DG PCC, as shown below:

A. $tg\phi = f(v)$, control of the tangent of the angle ϕ as a function of the voltage at the PCC;
B. $q = f(v)$, 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 four control laws analyzed are represented in Fig 1.

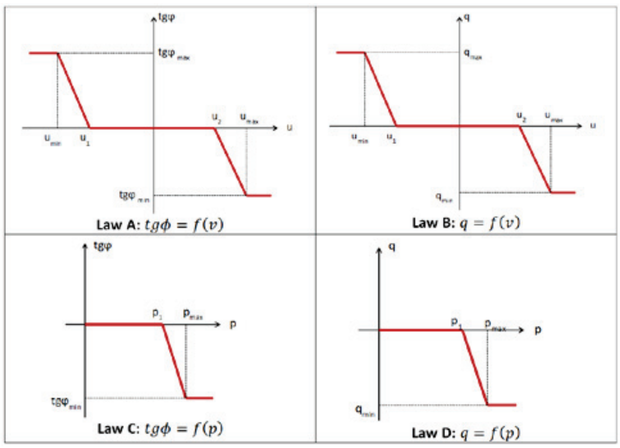

Fig. 1: Shape of the 4 control laws analyzed

Control Law B and Law C are included into the new CEI 0-21 standard.

Because of the high value of the R/X ratio of LV distribution networks the control laws presented below

978-1-4673-4430-2/13/$31.00 ©2013 IEEE

have only a partial effectiveness on the voltage quality and over-voltages can persist in critical cases.

In these cases, it can be necessary to limit the production of the real power of DG units in order to avoid the activation of the interface protection and the DG unit disconnection.

A. 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 analysis aims to analyze the performance of the proposed control laws on a selected LV feeder according to a simplified one-year analysis.

The test grid analyzed is reported in Fig. 2.

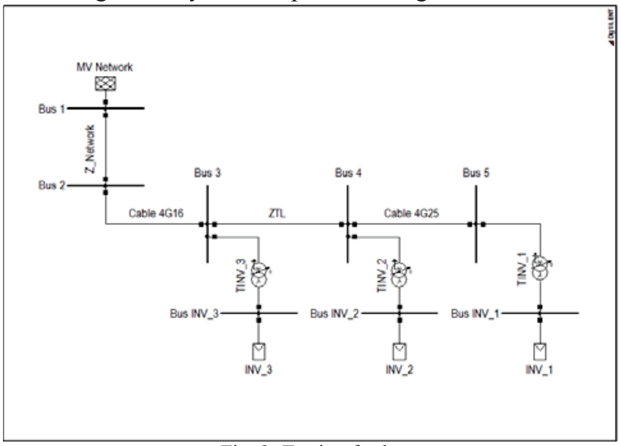

Fig. 2: Testing feeder

Three PV inverters were modeled: INV1 and INV2 (20 kW rated power) managed, according to the four control laws of reactive power, 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 LV Italian utilities [11].

Table I shows the annual Hosting Capacity (HC) index. Simulations are based on a one-year system operation and considering an overvoltage limit of +10% of the rated voltage (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 and the adoption of the reactive power control laws allows increasing the HC of the system.

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%

Control laws A and B, in which Q production 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 Q production is linked to the real power injections.

In Table VI the results of a power injection equal to 20 kW (for both INV1 and INV2) are shown, thus exceeding the HC feeder. The inverter INV3 is a 30 kW rated power load with an annual cumulative absorption of 29.2 MWh/year.

On the basis of these hypotheses, the performance of the four control laws are evaluated with regard to the following indices:

- h_{vio} [h]: annual hours of overvoltage violations;
- ΔEn_{prod_PV} [kWh]: annual energy production of the DG unit with respect to the reference value of 44136 kWh/year, which is equal to the case of unitary power factor operation of the PV plants and without any disconnection if over-voltages occur;
- ΔW_{grid_loss} [kWh]: energy losses in the gird with respect to the reference value of 3428 kWh/year, which are computed in case of unitary power factor operation of the PV plants and without any disconnection if over-voltages occur.

The simulations are carried out considering two possible operating conditions of the DG unit. In the first condition INV1 and INV2 are disconnected to the grid in case of over-voltages at the PCC by the Interface Protection System IPS (as required by Italian standard CEI 0-21), with consequent lack of production of the generator. In the second condition a real power limitation function was simulated.

According to the real power limitation the DG unit decreases the real power injection by steps of 10% of the rated power in order to avoid over-voltages, i.e. the tripping of the IPS.

TABLE II: SIMULATION RESULTS FOR P_{DG}=20 KW

		IPS tripping of DG unit		DG P Limitation	
	h_{vio} [h]	ΔEn_{prod_PV} [KWh]	ΔW_{loss_rete} [kWh]	ΔEn_{prod_PV} [KWh]	ΔW_{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%)

The results of Table II depict 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% compared to cosφ=1 condition) and lack of DG production (0.08% of lacking energy production with respect to the ideal case). Anyway, Law B increases the energy losses (+9.5%).

By means of the real power limitation, the lack of DG production is minimized.

Comparing the results previously obtained with the cosφ=1 operation condition (Table III), it can be concluded that Law C (mentioned in the CEI 0-21) has the highest energy benefits resulting in a 66 kWh of energy injected at the SS (third column of Table III).
The analysis carried out for the different control laws shows that it is possible to mitigate the over-voltages in the LV distribution network by exploiting the DG unit as reactive power resources decentralized along the distribution system.
Moreover, in the experimental campaign the effectiveness of different control laws and the stability of the network in the case of step-stress injection of active and reactive power were tested.

TABLE III: VARIATION OF ENERGY PRODUCTION WITH REAL P LIMITATION WITH RESPECT TO THE cosφ=1 CASE

	PV energy [kWh]	Grid losses [kWh]	SS energy [kWh]
Law A	+230	+197	+33
Law B	+283	+374	-91
Law C	+93	+27	+66
Law D	+49	+16	+33

IV. REAL POWER MODULATION SERVICES

As well as the reactive power modulation service, the DG power plant can modulate real power in order to support the frequency regulation capability and improve the system operation in case of relevant power unbalance. Energy Storage System (ESS) integrated with DG can ensure the margin of power required for the service.
Research concerning this topic has started focusing on numerical analysis carried out by software simulations.
A dynamic model of a Photovoltaic System (PV) integrate with an ESS, was developed with the aim to simulate its contribution to the reestablishment of the power balance among the network. The new apparatus, in the case of frequency deviations from the nominal value, modulates the power injections according to a droop function in order to contribute to the network stability (according to the ENTSO-E network code, Fig. 5).

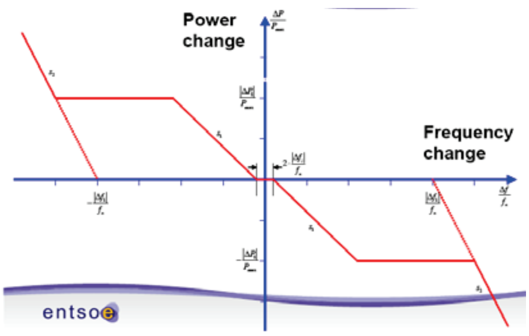

Fig. 3: ENTSO-E network code Real power modulation according to frequency deviation: Droop control

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}: 3% of the rated power;
- Minimum time to deliver the maximum capability: 15 minutes;
- Maximum time of full activation: 30 seconds;
- Maximum time of half activation: 15 seconds.

This control can be provided only if a suitable ESS is coupled with the intermittent energy sources. In this way, the storage system can ensure that part of the energy needed for the control function that cannot be provided by the renewable system itself.
A simplified network model was built in the PowerFactory DIgSILENT software (Fig. 6). The network model is a grid-connected system; it is connected to the 20 kV AC network through an MV/LV transformer (INVERTER-Trafo) and a grid following inverter (INVERTER) with 250 kVA rated power, which controls the real and reactive power injected at the AC side. The PV and the ESS are connected to the DCLink bus (DC-coupled system) with nominal value of 700 V and capacitance equal to 30 mF. The PV system injects its optimal power (MPPT is achieved), which is assumed constant and equal to P_{PV}=200 kW, whereas the DC/DC converter of the ESS (i.e. ESS Converter of Fig. 2) controls the voltage at the DCLink by modulating its power P_{ESS} in order to set the power balance according to the following equation:

$$P_{PV} - P_{ESS} - P_{AC} = C_{DCLink} \cdot V_{DCLink} \left(\frac{dV_{DCLink}}{dt} \right)$$

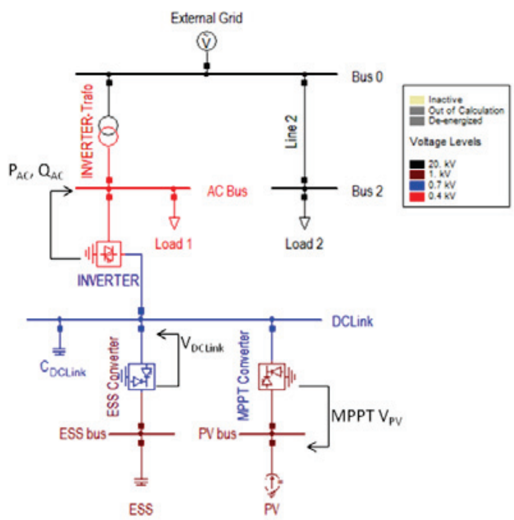

Fig. 4: Network scheme of the PV system integrated with an ESS in a DC-coupled system

A simple first order dynamic circuit was considered to model the charge and discharge phenomena of the ESS: it is modeled through an ideal capacitance (C=64.29 F) and an equivalent series resistance (R=1 mΩ); the values of the ESS parameters are defined in order to meet the minimum time to deliver the maximum capability P_{max},, which is equal to 7.5 kW.
The behavior of the ESS is analyzed by evaluating its response to a real one-day frequency oscillation of the

electrical system (Fig. 7) ([12]) imposed by the ideal voltage source External Grid of Fig. 6.

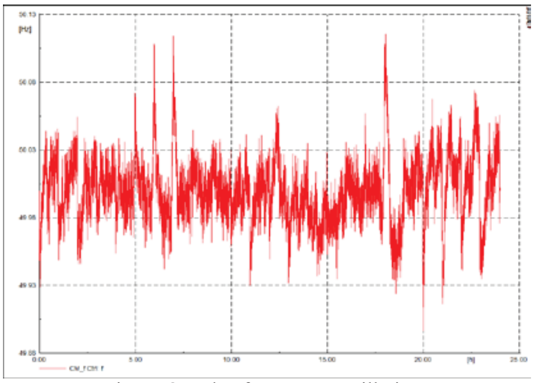

Fig. 5: One day frequency oscillations

The ESS injects/absorbs the power required to match the power balance at the DC-Link and provides the primary frequency control according to the droop control. The real power delivered by the ESS in compliance with the frequency control strategy is shown in Fig. 8. The power change owing to the frequency deviation with respect to the nominal value is computed according to the local strategy of Fig. 5.

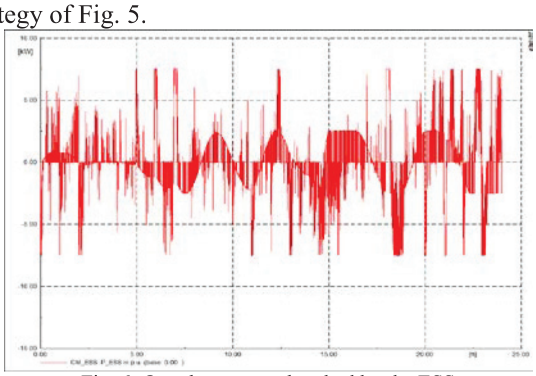

Fig. 6: One day power absorbed by the ESS

The voltage at the ESS represents the state of charge of the ESS: if the ESS injects power to the DC-Link (discharge phenomena) the voltage decreases, on the contrary in the case of power absorptions (charge phenomena) the voltage increases; the one-day voltage oscillations are shown in the graph of Fig. 9.

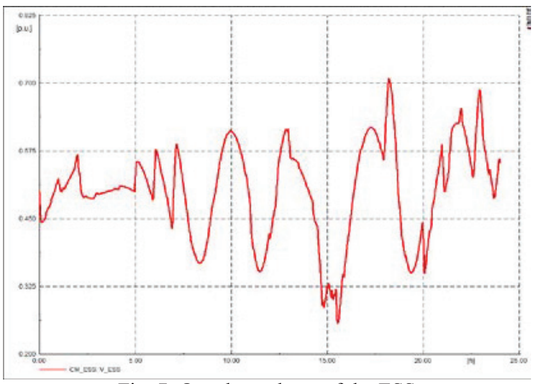

Fig. 7: One day voltage of the ESS

In the case of frequency oscillations the ESS is charged or discharged according to the droop curve; in this way it performs both a power mission for supplying energy in a short time period and an energy mission for guaranteeing the real power balance (primary frequency control).
A high penetration causes a reduction of the total rotating inertia of the system. For this reason, and even more in weak structural networks such as the Sicily and Sardinia electrical systems, the participation of DG in primary frequency regulation can provide synthetic/artificial inertia, which is necessary to increase the capability margin for the stability of the system.

V. ALPSTORE PROJECT

Preliminary results obtained by dynamic software simulations point to a quite interesting capability for the future design of experimental prototype; such a prototype will be tested in the AlpStore research project framework [13]. It is an AlpineSpace project: Partners in seven countries create master plans for the deployment of storages. Pilot tests will show the feasibility of mobile and stationary storage in public infrastructure, business parks, enterprises and smart homes. From there, guidelines will be derived for planners and decision makers. The Pilot application range from Renewable Energy monitor and forecast, Demand Side management, E-car charging process coordination and a stationary storage prototype, designed in order to provide an ancillary service (frequency regulation) to the main grid.
In particular, the Politecnico di Milano will carry out the proposed test application in cooperation with Euroimpresa, a local cluster of SME. Actually, Euroimpresa was founded in July 1996, from the constitution of the Legnano Reindustrialization Committee, promoted by the Province of Milan and City of Legnano [14]. Thanks to its activity in supporting entrepreneurs and enterprises with business development (start up, innovation and restructuring projects and internationalization), in 1997 Euroimpresa has been recognized as EC-BIC (Business Innovation Centre) and as a full member of EBN (European BICs Network). Euroimpresa objectives range from:

- promoting regional development by enhancing the value of Lombardy and its assets,
- supporting changes through needs analysis,
- spreading of advanced technologies, news products and process innovation,
- sustaining integrated development of the territory in order to face International competition,
- reinforcing employment and equal opportunities policies by encouraging daily training and small entrepreneurship,
- constitution of networks with European partners in order to exchange knowledge and best practices.

978-1-4673-4430-2/13/$31.00 ©2013 IEEE

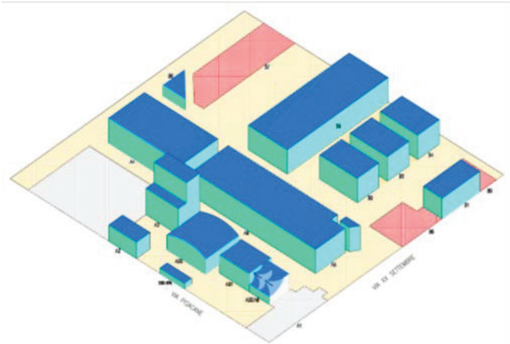

Fig. 10: Map of the TechnoCity area (blue buildings represent SME, grey dashed buildings repsent Euroimpresa officies, red dashed area represent new buildings under construction; the total area cover more than 25000 m^2)

The Pilot Application is based on the monitoring and control of the electric energy needs of the technocity (industrial area sited in Legnano, North-West of Milan city), coordinating with respect to different goals, power flows due to photovoltaic production (120 kW on the roof) and consumption (the area is connected to the main grid by two medium voltage/low voltage transformers that feed the lighting and thermal apparatus, moreover each SME has its own meter devoted to energetic processes).

VI. Conclusion

At present, in the existing network operation, DG units are causing many technical problems due to the fact that the conventional power system was not designed for such operation. However, DG units can also provide different ancillary services for the network operator, meaning DG can be transformed from being a part of the problem into a part of the solution.

The paper focuses on two main applications of dispersed generation in the provision of ancillary services of the electrical system, and technical solution are proposed and tested.

The proposed approach consists in exploiting ancillary resources spread along the network instead of using centralized resources.

After this theoretical study the project, named AlpStore, will have an experimental application on field, in an industrial area sited in Legnano (North-West of Milan city).

VII. Acknowledgment

AlpStore is funded by the Alpine Space Programme 2007-2013, as a part of the "European Territorial Cooperation". (http://www.alpine-space.eu/).

References

[1] J.A. Pecas Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, N. Jenkins, “Integrating distributed generation into electric power system: A review of drivers, challenges and opportunities”, Electric Power System Research, 77 (2007) 1189–1203, 2006, Page(s): 1-15.

[2] D. Menniti, M. Merlo, N. Scordino, N. Sorrentino, F. Zanellini, “A DSO-orientated mathematical model for dispersed generation management on MV networks”, in *Proc 2012 IEEE PES General Meeting*, July 2012, San Diego (USA).

[3] M. Delfanti, D. Falabretti, M. Merlo, “Dispersed generation impact on distribution network losses”, Electric Power Systems Research, Volume 97, 2013, Pages 10-18;

[4] M. Delfanti, D. Falabretti, M. Merlo, D. Moneta, “MV networks reconfiguration for losses reduction”,2012 IEEE International Energy Conference and Exhibition, ENERGYCON 2012, Pages 318-324.

[5] A. Berizzi, C. Bovo, M. Delfanti, M. Merlo, M.S. Pasquadibisceglie, “A Monte Carlo approach for TTC evaluation“, IEEE Transactions on Power Systems, Volume 22, Issue 2, May 2007, Pages 735-743

[6] T. G. Hazel, N. Hiscock, J. Hiscock, “Voltage regulation at sites with distributed generation”, IEEE Transactions on industry applications, Vol. 44, No 2, Digital Object Identifier: 10.1109/TIA.2008.916749 March/April 2008, Page(s): 445-454.

[7] M .Braun, C. Ma, “Improving capacity utilization – Low voltage grids with photovoltaic penetration”, Cigrè International Symposium; Bologna, 13-15 September 2011, Page(s): 1-8.

[8] European standard EN 50160 “Voltage characteristics of electrical supplied by public distribution systems”, CENELEC TC 8X, 2008.

[9] www.terna.it

[10] Berizzi, A., Bovo, C., Delfanti, M., Merlo, M., Pasquadibisceglie, M.S., “A Monte Carlo approach for TTC evaluation”, IEEE Transactions on Power Systems 22, pp. 735-743.

[11] M. Gallanti, M. Merlo, D. Moneta, P. Mora, G. Monfredini, V. Olivieri, “MV network with Dispersed Generation: voltage regulation based on local controllers”, paper 0934, 21th International Conference on electricity Distribution CIRED, Frankfurt, 6-9 June 2011.

[12] Berizzi, A., Bovo, C., Delfanti, M., Merlo, M., Pozzi, M., Sforna, M., Reactive power management in the Italian system. A proposal for an economic compensation, Proceedings of the Mediterranean Electrotechnical Conference - MELECON 2006 , art. no. 1653246 , pp. 910-914.

[13] F.Lanzi, M. Merlo, G. Callegari, P.Capurso, R. Zaottini, “Wind Power Generation Impact on the frequency regulation: Study on a National Scale Power System”, ICHQP 2010, Bergamo (Italy)

[14] 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, CEI, Milan.

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

[16] Netzfrequenzmessung. Beispieltag der Netzfrequenzmessung mit Minuten- und Sekundenwerten. www.netzfrequenzmessung.de, 8 March 2011.

[17] www.alpstore.info

[18] http://www.euroimpresa.it/en