STORAGE APPLICATIONS FOR SMARTGRIDS

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Abstract—In the framework of the transition towards the new paradigm of electricity grids, the exploitation of intrinsic energy storage or deliberately installed storage systems (either thermal or electric) plays a major role in enabling the actual controllability of the various sources and loads connected to the system. Controllability, for different purposes, is the key factor which characterises a Smartgrid compared to a traditional energy system.

This paper presents a systematic approach to the services that a storage system is able to provide in an electric power system and shows how such systems can be actually designed and built. In several research projects the University of Pisa installed storage devices for different purposes showing the effectiveness of the contribution they give. This paper also shows how particular loads, which are connected to the grid through a power conditioning device, can provide important ancillary services for the grid.

Keywords— Smart Grids, storage systems, transport systems, demand response, virtual power plant

1. Introduction

In recent times, several issues pushed towards the transition to a new paradigm for electricity grids which is now worldwide recognized as Smartgrids. The key factors have been [1, 2, 3]:

- the increasing share of renewable sources which are continuously being connected to the system and which have a distributed nature
- increased demand for improved power quality and reliability
- the current transition from a passive distributed grid to an active one
- the availability of new reliable communication systems
- the development of a deregulated electricity market where classical electricity users become energy customers who need information for properly managing their energy needs and who can be providers of

grid services

The most important characteristic of a Smartgrid is the possibility of controlling (with different purposes) the various sources and loads connected to the grid, with the final target of improving the overall efficiency in the exploitation of prime sources and the quality of power supply.

In this framework, on the generation side, an increasing amount of different kinds of distributed sources is continuously being installed in both residential and industrial areas throughout the world. In many cases, these systems are operated without considering their interaction with the rest of the system and even with the other sources and loads connected to the same local network. On the demand side, a class of electricity users exists which can easily adapt their behaviour to the new vision of the grid, where not only the producers are requested to be active in the system, but also consumers with an "intelligent" and "smart" behaviour are needed [4, 5]. Urban electrified transport systems, either directly supplied from the grid or exploiting onboard storage systems, interact with the grid with advanced interfacing systems where power conditioning devices exist [6, 7, 8].

A major role in this transition will be played by the use of storage, which not only means addition of electricity storage devices, but also utilisation of the intrinsic energy storage, such as the thermal energy stored in the hot water of a heat distribution system, the water storage of water distribution systems, the compressed air or steam storage in industrial processes and so on.

The paper presents a systematic approach to the services that storage systems can provide and shows the main results of research project demonstrating the profitability of the application of storage in various scenarios with different targets. Firstly, it shows how a properly sized storage device can provide services [1] for the grid when installed within a large renewable plant, and secondly, it presents a management tool applied to a smart user (a LV user including different kinds of electrical and thermal generating devices as well as thermal and electrical storage) which enables optimum schedule of the exploitation of the sources. Thirdly, it demonstrates how a storage system can be coupled with a simple urban transportation system to improve its interface with the grid as well as to optimize its power profile. Finally it shows that adding some storage for

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recovering the braking energy in a tramway system gives enables saving up to 30% of the primary energy needed in a cost effective way.

2. Network services from a storage system

Depending on the interface and the possible presence of storage, an active user can provide several functions for the network; they can be mainly classified as “power services” and “energy services”. The former refer to services involving power exchanges with the network having small durations up to a few minutes. The latter involve longer and sustained power exchanges. In different words, the ratio between energy and power for a “power service” is in the range between seconds and a few minutes, while for an “energy service” is from some minutes up so several hours.

Although the border line is rather vague, a different way of classification involves the characteristics of electrochemical storage used. When the designer sizes the storage system (the batteries) he has to choose the capacity in terms of rated energy stored. For each technology a given value of rated energy corresponds to a maximum power which can be exchanged. Power service usually means that the minimum storage volume needed to make it able to deliver the needed power is enough to enable the battery to provide the relevant energy. Energy service means that more storage must be added, to the minimum valued defined above, to supply the power requested for a longer time. For instance, if we want to deliver 1MW for 5 seconds with Li batteries, roughly 200kWh of storage is needed to ensure the battery can actually deliver the needed current. The energy delivered is just 1kWh. But if we want to deliver 1MW for 1 hour, at least 1MWh of storage must be installed which would even be capable of deliver up to 5MW for a few seconds. In the first case the battery is sized depending upon the power it must deliver, in the second case upon the energy.

In any case, the service provided can involve one or more of the following aspects: Security, Power Quality, Access to the network, Energy efficiency. All these aspects have their own economical value which, in many cases, if correctly remunerated, could alone make the system worth it [8, 9].

Depending upon the different possible applications, the use of integrated or purposely installed storage systems, enables the grid user (either a generator, a load a combination of both up to a Virtual Power Plant (VPP)) to improve his own performance both on the economical and energy efficiency side as well as in term of services to the grid.

Although only partly recognized, each service has its own value which, in several cases, fully remunerates the investment of installing a properly sized storage system. Many reports exist [10, 11] which assess the value that each service has for the entire energy system and which highlight that these services should be remunerated according to real benefit they provide. A summary of the different results is done in [9] and shown compactly in table 1.

Table 1

As far as the authors know, in the majority of deregulated systems these services are not explicitly remunerated, at least on distribution networks. In many weak grids, anyway, participating in congestion resolution and voltage regulation is in the direct interest of the prosumer, whose power profile would be otherwise curtailed by the DSO due to network constraints.

This paper will show how these services can be actually performed in some examples which have been chosen for some joint research projects involving the University of Pisa as well as some industrial and research partners.

2.1. Power services

2.1.1. Security

Significant benefits can be achieved in terms of:

- Peak shaving: a share of the load can be fed by the storage for short periods, thus reducing the impulsive requests of power from the network; positive effects concern the adequacy of the distribution and transmission system (deferral of transport capacity);
- Net congestion resolution: the quick correction of an overload, before generation being redispatched or network reconfigured, can be basically considered a power service;
- Islanding: the use of storage for demand modulation enables functions similar to primary regulation, thus facilitating the island to maintain the balance between production and load and during re-paralleling operations; in emergency conditions, large tolerances are accepted for system frequency, then security aspects overcome the usual power quality requirements.

- Ramp: rapid load variations, which could not be followed by conventional production units, can be curtailed by storage systems.
- Black start: installing storage devices close to electric transport systems, the trains could be quickly put in safe, even in the absence of electricity from the network. Afterwards, the storage could participate in the system restoration, energizing some paths or feeding the auxiliary services of small-size power plants.

2.1.2. Power Quality (PQ)

With adequate converters and storage devices, Power Quality can be significantly increased by:

- reducing short-term interruptions;
- participating in the frequency regulation, in systems conceived for islanded operation;
- providing active filtering functions, by means of a forced commutated inverter and a small storage (at most a well-sized condenser). It's one of the most promising services, in the new vision of smart grids;
- participating in the voltage regulation, by means of a modulation of reactive power production or consumption. Depending on converter's dynamic performances, also dips and sags can be compensated. In low voltage distribution networks, where the real part of grid impedance is not negligible, also real power compensation is required for an effective voltage regulation;
- reducing flicker phenomena, caused by industrial loads or intermittent sources like wind.

2.1.3. Access

From the point of view of the network operator, peak shaving functions can increase the transport capability margin available for new users, thus deferring new investments; on the demand side, this logic can be applied to make the load profile more compliant with the network requirements in terms of predictability and flatness, thus facilitating the access of the user to the system.

2.1.4. Energy efficiency

It is basically an energy service (see below), although some contribution can be given even in very short operating times.

2.2. Energy services

As mentioned above (at the beginning of section 2), storage devices installed beside the load for power services are usually sized in terms of power performance ; the energy capacity, resulting from the power size and the storage technology, is usually enough (or in surplus) for the service requirements, considering the short use of the storage. Besides, this kind of design and operation results in cycles with a small depth of discharge (DOD) for the storage device, thus lengthening its operational life.

By accepting a higher DOD or connecting more storage without increasing the size of the inverter, interesting functions can be provided for the grid, which can be classified, because of their duration, as “energy services”. The cost effectiveness of such investments should be carefully evaluated, comparing the marginal cost of the additional storage (whose converter already exists) and the revenue obtained for the services provided.

2.2.1. Security

A storage system can provide the following functions:

- Load levelling: the load profile is made flatter over a long time horizon (a day, a week), using a storage system that is charged during off-peak hours, while providing electricity during peak hours. The capacity of the generating system to securely meet the load is increased.
- Valley filling: this is a sub-function of load levelling specifically conceived to avoid nightly over-generation phenomena, when the load decreases below the technical minimum of spinning generating units
- Peak shaving: this is a still a sub-function of load levelling used to reduce the need for peak generating units.

2.2.2. Power Quality

Large storage systems could cope with medium and long interruptions.

2.2.3. Access

Peak power aspects are usually the leading factors in access issues, but when additional power is required for long durations, also the energy size of the storage becomes crucial. For instance, this is the case of a building site that for many consecutive hours needs a higher power than the value available from the network; a mobile storage system, charged during the night, could provide daily additional power to fully meet the load, thus avoiding new line capacity installation.

2.2.4. Energy efficiency

A significant change in the load profile can modify the operating point of the system, increasing the conversion efficiency of the generating units or reducing the grid losses.

3. Storage and renewable sources

During the last two years a partnership of universities and industrial operators has developed a research project (called "Smart Grid Navicelli" or simply Navicelli) funded by the Tuscany region authority, focused on applying optimized management tools to an industrial district with different kind of generators (wind, PV, combined heat and power (CHP)) jointly with the installation of electrical and thermal storages.

This project involved an industrial district hosting shipyards, commercial and office buildings, an innovative storage system has been installed on the MV network within a large PV plant [12]. Two storage systems were part of the project: a large 1-MW system connected on the MV grid in parallel to a PV system and a small 15-kW system connected to the LV busbar of a "Smart User" which will be described in section 4.

The first storage system was installed with the aim to improve the integration of the large 3.7-MW PV plant and to provide the grid with regulations services. Lithium batteries have been adopted as they are able to deliver large amounts of power with relatively small energy size.

The system has been designed and built for a converter rated power of 1 MVA (composed by three 250-kVA modules, peaking at 350 kVA). The storage is able to deliver 1 MW for eight seconds. Lower amounts of real power can be supplied for longer periods. Reactive power can be always delivered up to the maximum rating of the converter and depending on the real power demand.

Figure 1

The system is also able to perform active filtering of harmonics up to the 11th order at the interfacing section of the grid. This function could not be tested in this phase of the application, since the only user-source connected downstream the inverter is the 3.7MW PV system which does not generate these harmonics.

To make it capable of operating both in parallel to the grid and on a stand alone system supplied by the local sources, a real power vs frequency and reactive power vs voltage droop control has been designed and implemented, as hypothesised in [13] and reported in the figure 2. The values of f_0 and V_{ref0} in figure 2 define the real and reactive power the system should exchange with the grid (at rated grid frequency and voltage) and are defined to achieve the best energy and economic performance (e.g.: store energy during low price hours and release at peak hours, or store energy in case of local grid congestions). As the frequency and the voltage at inverter terminals change, the inverter will increase or decrease the real and reactive power exchanged according to the droop characteristics so participating in primary frequency control and voltage regulation. The system has been designed to be installed inside two standard containers for easing the installation procedure.

Figure 2

The storage system can perform several services [8] depending on the control signals it receives. Properly defined real and reactive power set-points can be given through an external controller for optimizing the PV system generation profile according to the schedule contracted on the market or to maximize the profit from selling energy during peak-price hours. But even without any external reference signal, the droop control concept makes the converter supply a proper amount of power depending on the grid condition thus contributing to the grid frequency and voltage control. It can even support the islanding of the PV system on a local load, by supplying the needed voltage and frequency references to the PV converters for the time needed to change the balance between generation and load [13].

When, in the next years, the shipyards, commercial and office buildings, which are currently under construction and which experienced some delays, will be completed and the commercial and industrial activities will reach their operating regime, the storage management system will be updated to optimize the overall energy service of the district. Also additional batteries (without increasing the converter size) could be installed to increase the amount of energy which can be moved.

The figures below show the result of some preliminary operating tests on one of the 250-kVA modules for checking the performance for grid frequency support. Figure 3 clearly shows the operation of the droop control during the fluctuations of the grid frequency. The frequency fluctuation shown is just ±20mHz and is the usual frequency fluctuation of the European interconnected system due to plant switching and primary frequency regulation system. The inverter module was operating with a setpoint of 30kW charging the batteries. The droop value of the inverter controller was set to 2%, which means that 20mHz of frequency deviation implies a power response of 5kW on a 250-kVA module, as proven in the figure. We remark that the response speed is extremely quick (power and frequency are exactly in counter-phase) and that a 2% droop is very low compared to what usually asked to rotating power plants which is 5% which means a larger contribution compared to a rotating plant having the same size. The contribution is also bi-directional and can be made available also during low frequency transients. The contribution of distributed storage systems could largely compensate the continuously decreasing of the available regulation capacity due to the increasing share of renewable sources which, only if properly controlled, can at least contribute during over-frequency transients.

Figure 3

4. Storage for energy management of a Smart User

The second storage system installed within the Navicelli research project relates to the operation of a Smart User. A Virtual Power Plant has been conceived and realised by adding a cogeneration system as well as a thermal and electric storage system to the already existing PV and micro-wind sources supplying the headquarters of Navicelli SpA. In this case the VPP includes a 25kW PV generator, a 6-kW vertical axis wind turbine, a 19-kW$_e$/40-kW$_t$ gas cogeneration unit, a 15-kW/8-kWh electric storage, a 5-m^3 heat storage (Figure 4)

Figure 4

The key factor for this application is the development of an optimized thermal and electrical scheduler of the various sources which enables the VPP owner to maximise his energy and economic efficiency [14]. The structure of the Smart User is depicted in figure 5:

Figure 5

The thermal part of the Smart User, connected to the lower busbar, is basically composed by a load, that can be fed by the CHP, the boiler or a thermal storage device (TS). If the thermal production of the CHP exceeding the load cannot be absorbed by the storage (due to power or energy limitations), the surplus P_{sur} is released to the atmosphere by means of a heat exchanger.

The electrical part is divided into two sections. The first one is called "internal" and corresponds to a conventional autoproducer, whose border with the distribution grid is the internal Point of Common Coupling ("internal PCC - p_{cci}"). This part of the model, which is connected to the central busbar, is mainly composed by an electrical load, an "internal" renewable energy source (IRES) and/or of an energy storage device (ES). Many feed-in tariffs applied worldwide do not reward the overall energy produced by particular kinds of RES (like very small wind farms), but only the energy amount injected to the grid. In this case, installing such plants inside the VPP internal part would restrict the feed-in tariff only to the production exceeding the local load, if there is any; thus the producer will optimize his investment installing such plants in the surroundings - not internally-, using another PCC; hence the terminology "External Renewable Energy Sources - ERES" and "external PCC - p_{cce}".

In the specific case of the Navicelli Smart User, the VPP includes a 25-kW PV generator, a 6-kW vertical axis wind turbine, a 19-kW_e/40-kW_t gas-fired cogeneration unit (technical minimum: 7.5 kW_e; rated electrical efficiency: 30%), a 15-kW/8-kWh electric storage (round trip efficiency: 90%), a 25-kW/100-kWh heat storage (round trip efficiency: 90%) and a 25-kW gas-fired boiler. An electric and thermal load, whose peak demand are respectively 60 kW_e and 20 kW_t, are also present.

A mixed-integer linear algorithm [15, 16, 17] has been implemented in a power scheduler [14], that assumes as an input the expected power pattern of the electrical and thermal load and the forecasted power pattern of RES; with time steps of 15 minutes or one hour, the power dispatcher calculates the daily optimal operation of energy storage devices and of dispatchable generation (conventional power plants, CHPs, boilers), in order to meet the electrical and thermal load and maximize the VPP net daily profit. This takes into account the costs for buying electricity and fuel, the revenues from selling the electricity surplus to the market, and subsidies for RES, which can be applied to the produced energy (internal RES) or to the energy injected into the grid (external RES).

The optimizer can be run in the afternoon before the day of energy production, as well as for infra-daily rolling corrections. The tool can also suggest load shedding procedures, or RES curtailing, in case of a severe shortage of transport capacity, like in islanded operation. In grid-connected operation, the presence of thermal and electric storages increases by 8-10% the daily cash flow of the Navicelli Smart User (-320 €/day if passive user, -240 €/day with local generation, -215 €/day with energy storages); this is basically obtained by optimizing the timing of energy purchase and sale with respect to the load requirement and to the solar and wind production, as well as exploiting the combined presence of thermal and energy storages. This latter discloses new opportunities for the operation of the CHP system (combination of thermal and electrical load following), thus suggesting scheduling profiles that are not always identified by heuristic algorithms [18].

Presently, a Large Scale VPP is also being implemented in the Navicelli area, including several Smart Users similar to the one previously described and installed along the same MV distribution line; the main idea is that a Scheduling Coordinator will optimize all distributed energy resources in order to maximise the revenues of the entire cluster in a cooperative scenario, especially under shortage of hosting capacity [19, 20, 21, 22].

Large Scale VPPs can be also able to respect an "aggregate behavior" compliant with the grid requirements.

For all these reasons, an optimal dispatching algorithm is being implemented that could constitute added value:

- for the scheduling coordinator, in order to maximize the total revenue of the VPP: in the event of severe constraints, the total income could be significantly higher than the one obtained leaving each DER free to decide its behaviour. For example, two plants could be in competition to deliver their full power to the grid because there is a grid bottleneck: the scheduling coordinator can find a strategy whereby a small reduction of the first plant revenues delivers big market opportunities for the second plant (whose nature is better remunerated under the present market conditions), with a positive net economic balance.
- for the DSO, in order to predict the VPP behaviour and calibrate demand response initiatives to cope with variable network constraints.

Three kinds of operational procedures are being implemented in the algorithm: a) free: the VPP is freely allowed to exchange electricity with the network, simply respecting technical constraints (voltage and power flow); b) islanded operation: the flow to and from the electrical substation, which feeds the MV feeder, is strictly compelled to be null; c) balanced operation: the VPP receives an additional profit if the power flow exchanged with the substation matches an hourly pattern, within a given tolerance (±5%).

5. Transportation systems

All the electrified transport systems are supplied through a power conditioning device which in turns feeds the motor itself (as in cable cars, lifts or moving walkways) or the supply line (as in underground, railway, light railway and trolleybus systems) or charges the onboard storage system (as in electric road vehicles or industrial vehicles). The possibility to adapt the control system of the grid interface to provide the grid with several services, as well as the chance to add some storage system, makes these users good candidates to integrate demand response features.

5.1. Cable car systems

The first actual application concerns a cable car transportation system where the University of Pisa developed a research project jointly with ENEA, the manufacturer EEI, and ATB, the transportation utility of Bergamo. The “San Vigilio” cable car in Bergamo (Italy) connects the lower part of the town with its historical centre, located over a hill with a 620-m long track with a total difference in altitude of 90 m which is covered by a single car.

The typical operating profile is shown in Fig. 6. The maximum demand is 160 kW along the steepest section and reaches 200 kW with fully loaded car.

The drive always demands reactive power from the grid with a power factor close to 0.7, both during uphill and downhill operation, as theoretically requested by a thyristor bridge operating with α close to 45°.

The supply system is a source of large amounts of current harmonics (see figure 7). Its intermittent operation also reversing the power demand caused flicker phenomena on the loads connected near the supply system.

Figure 6

Figure 7

The new supply scheme which has been developed includes a lithium battery storage system with a storage capacity of 18 kWh. The scheme adopted, shown in fig. 8, includes the motor drive made of a grid commutated thyristor Graetz bridge and a DC motor. The cable car operator, also for complying with cable car regulation requirements, decided to keep the original DC motor and to refurbish the supply system. It was therefore improved with a Li-ion storage device and an active filtering system.

Figure 8

The new system performs the following functions:

- fixing a limit of 100 kW to the maximum power from the grid
- enabling energy recovery during downhill trips
- active filtering of the current of the thyristor based converter
- compensating the reactive power needed by the drive without exciting resonance frequencies introduced by static capacitors
- providing dynamic services to the grid

Figure 9 shows a real recording of the power exchanged by the system (single phase power) during a round trip. Its clear that during the downhill trip all the energy is stored in the batteries, and is then released during the next uphill trip. The total energy exchanged by the batteries during a trip is around 1 kWh (depending on the car loading condition). In this way the maximum difference between the maximum and minimum (negative) power exchanged with the grid is strongly reduced from the original 300 kW down to just 100 kW

Figure 9

Concerning harmonic current filtering, figure 10 shows the current in the three different sections during a downhill trip. It highlights how the storage system not only compensates the power generated by the motor drive, but also injects a current which cancels the low order harmonics of the motor drive current itself. The current spectrum at the drive terminals reveals a very large 5th order harmonic (60 A with respect to a fundamental of 170 A) and a large 11th order one (18 A). The current injected by the storage inverter, in addition to fully compensate the power demand (1st harmonic), cancels the 5th and 11th harmonics which are reduced to 7 A and 2 A respectively. The 29th and 31st harmonics are slightly increased due to the operating frequency of the PWM controller of the inverter itself. These high frequency harmonics do not affect the distribution grid since are filtered by the grid components and, if needed, could easily be filtered with traditional filters.

Figure 10

The project clearly demonstrates the technical feasibility of solutions adopting storage for improving the performance of transportation systems and for supplying useful services to the grid. Unfortunately, although worldwide studies indicate an economical value for these services which would largely remunerate the investment, the present connection rules and tariffs penalize storage projects, basically because power tariffs are conceived for accounting the peak consumption of traditional customers, and never remunerate the power services provided for the grid.

In this case the main benefit achieved by the cable car operator is the chance to recover the energy otherwise wasted during the downhill trip [9]. This benefit sums to around 1.5k€ per year, facing an investment cost of 15k€. Its clear that the return time of the investment would be too long, but, considering also some additional contributions in terms of reactive power regulation, peak shaving and harmonic filtering, the application becomes cost effective.

5.2. Application to a tramway system

In many urban areas, the use of light rail transportation systems such as tramways is being recovered for complying with the needs of modern life mobility needs with energy and environment effective solutions. These systems have a high well to wheel efficiency, a low moved mass per passenger and enable regenerative braking by sending energy back to the grid. However, in many cases the substations which supply the contact line can not be reversed and braking energy can be recovered only when vehicles different from the ones that are braking, located in their vicinity, are able to absorb some energy. A solution, which has been investigated through detailed simulation [23] of a real line, is the use of storage systems connected to the DC busbar of one or more substations directly or by interposition of a DC/DC converter. This application has been analyzed with the transport authority of Bergamo and concerns a 12km long tramline supplied by 10 substations, in which from 3 (holidays) up to 10 (peak hours) trams operate the same time. Since braking times are in the order of 10-20 s, the most frequently proposed solution takes advantage of supercapacitors [24, 25]. However, supercapacitors typically require the presence of a DC/DC converter, since the charge/discharge processes imply rather large voltage variations.

On the opposite side, the recently developed high power lithium batteries have the advantage that they can be directly connected to the line, so that costs, space occupation and complexity of the DC/DC converter are avoided [26].

Different possible configurations have been analysed:

- Trams dissipate all the braking energy in on-board resistors
- Trams send their braking energy into the contact line as long as the contact line voltage does not overcome the maximum limit of 900 V
- As above, but adding one 100-kWh storage system based on lithium batteries in correspondence to the substation situated in the mid of the tramline.

Detailed simulations showed that the yearly energy demand from the grid decreases from 3100 MWh in case of energy dissipation, down to 2870 MWh when enabling regenerative braking and to 2610 MWh when the storage system is used.

These figures show a net saving of around 40 k€ per year thanks to the effect of the storage system. The cost estimate for the 100-kWh battery system including all the additional components is 50 k€.

The actual advantage is so distinct that the tramway operator decided to evaluate actual installation of the device.

Further studies have then shown that the energy saving increases if more storage systems are installed at the different substations with different controlling strategies [27]. The summarising table 2 shows the results referring to an increasing number of 100-kWh storage systems installed at the various substations. Results have been obtained with the detailed simulations described in [23] and the yearly energy absorbed from the grid was calculated for each case supposing to have from zero up to ten 100-kW storage systems installed evenly distributed across the ten substations. (i.e. case 1: in substation 5, case 2: in substations 3 and 7 and so on). The reference value of 2869 MWh refers to the system without any storage installed with regenerative braking allowed up to a contact line voltage of 900 V. When the voltage overcomes this value the reminder of braking is dissipative. This concept is still valid when storage is installed. The possibility of injecting power into the batteries enable the voltage to be better controlled and avoid dissipative braking.

Table 2

It’s clear that it’s worth installing up to four storage systems to get the maximum benefit. Each of them enables saving around 250MWh/y of energy (1049MWh with four systems), that is around 40k€ savings for each of the storage systems installed up to four. Any additional storage system would increase the actual energy saving but the incremental cost would overcome the value of the saved energy.

It’s worth noticing that this application is not to be regarded as a simple energy efficiency increase. The power profile demanded to the grid is largely smoothed and peak power can be reduced.

6. Conclusions

The importance of storage for profitable and effective operation of modern power systems is continuously increasing. When the services that storage systems can provide are clearly defined, and a correct assessment of the actual economical value of each service is carried out, the experience gathered clearly demonstrate that correctly-sized storage systems can effectively pay for the investment made for their installation.

The results of the several year experience of the University of Pisa in various fields of commercial application of storage devices have also demonstrated the technical and economical feasibility of adding storage systems to domestic users, renewable generation plants and transportation systems.

Depending on the applications, results showed that storage systems are paid in some cases by the value that the energy gains when moved from one period to another and, in other cases, by the value that services have.

It is worth finally remarking that the costs of storage systems has largely decreased during the last decade driven by the increasing diffusion of batteries on electrical and hybrid vehicles. Several services that few years ago were below the economical effectiveness now clearly remunerate the investments.

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8. References

[1] G. Strbac, “Electric power systems research on dispersed generation” Electric Power Systems Research, Vol 77, Issue 9, September 2007, pages 1143-1147.

[2] J.A. Pecas Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, N. Jenkins, “Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities” Electric Power Systems Research, Vol 77, Issue 9, September 2007, pages 1189-1203.

[3] R.Giglioli, D.Poli, “Small-scale biomass-fired cogeneration, pellet production or district heating: new criteria for selecting the most profitable solution”, International Review on Modelling and Simulations, IREMOS, Vol.6 Issue 3, June 2013.

[4] M.Giuntoli, D.Poli, “On the possible use of probabilistic techniques for purposes of short-term load dispatching”, International Review of Electrical Engineering, IREE, Vol.8 Issue 4, August 2013.

[5] P.Palensky, D.Dietrich, "Demand side management: Demand response, intelligent energy systems, and smart loads", IEEE Transactions on Industrial Informatics, Vol.7 Issue 3, August 2011.

[6] D.Pudjianto, M.Aunedi, P.Djapic, G.Strbac, "Whole-systems assessment of the value of energy storage in low-carbon electricity systems", IEEE Transactions on Smart Grid, Vol. 5 Issue 2, March 2014.

[7] P.Sinhuber, W.Rohlfs, D.U.Sauer, "Study on power and energy demand for sizing the energy storage systems for electrified local public transport buses", 2012 IEEE Vehicle Power and Propulsion Conference, VPPC 2012, Seoul, South Korea, 9-12 October 2012.

[8] S.Barsali, A.Bechini, R.Giglioli, D.Poli, 2012, “Storage in electrified transport systems”, IEEE Energycon 2012, September 9-12, Florence, Italy.

[9] S. Barsali, R. Giglioli, D. Poli, and F. Vellucci “Demand Response of urban transport systems: a help for deploying the new Smart Grid paradigm”, Cigré International Symposium The Electric Power System of the Future - Integrating supergrids and microgrids, Bologna, Italy, September 13-15, 2011.

[10] CIGRÉ WG C6-11, Brochure 458, “Electric energy storage systems”, April 2011.

[11] Sandia National Laboratories, “Energy storage for the electricity grid: benefits and market potential

assessment guide”, http://prod.sandia.gov/techlib/access-control.cgi/2010/100815.pdf

[12] S.Barsali, G.Caridi, M.De Chirico, L.Ferrari, R.Giglioli, M.Giuntoli, S.Magnani, M.Pentolini, G.Petretto, D.Poli, S.Scalari, “Experience on energy management in an industrial district”, 22nd International Conference on Electricity Distribution, CIRED 2013, 10-13 June 2013, Stockholm, Sweden.

[13] S.Barsali, D.Poli, “Innovative techniques to control inverter interfaced distributed generators” CIRED 2003, Barcelona, Spain, May 12-15, 2003.

[14] M.Giuntoli, D.Poli, “Optimized thermal and electrical scheduling of a Large Scale Virtual Power Plant in the presence of energy storages”, IEEE Transactions on Smart Grid, Vol.4 Issue 2, June 2013.

[15] P.Lombardi, M.Stotzer, Z.Styczynsky, A.Orths, "Multi-criteria optimization of an energy storage system within a Virtual Power Plant architecture", Power and Energy Society General Meeting, 2011 IEEE, 24-29 July 2011, San Diego, California.

[16] M.Brau, "Technological control capabilities of DER to provide future ancillary services", International Journal of Distributed Energy Resources, Vol.3 n.3 (2007).

[17] A.Richards, J.How, "Mixed-integer Programming for Control", Proceedings of American Control Conference, 2005.

[18] C.Hinrichs, J.Bremer, M.Sonnenschein, "Distributed hybrid constraint handling in large scale virtual power plants", 4th IEEE/PES Innovative Smart Grid Technologies Europe, ISGT Europe 2013, Lyngby, Denmark, 6-9 October 2013.

[19] N.Ruiz, I.Cobelo, J.Oyarzabal, "A direct load control model for Virtual Power Plant management", IEEE Transactions on Power Systems, Vol.24 No.2, May 2009.

[20] T.Sowa, S.Krengel, S.Koopmann, J.Nowak, "Multi-criteria operation strategies of power-to-heat-Systems in virtual power plants with a high penetration of renewable energies", 8th International Renewable Energy Storage Conference and Exhibition, IRES 2013, Berlin, Germany, 18-20 November 2013.

[21] M.Zdrili´c, H.Pandˇzi´c, I.Kuzle, "Virtual Power Plant dispatch optimization using linear programming", 2011 10th International Conference on Environment and Electrical Engineering (EEEIC).

[22] M.Zdrili´c, H.Pandˇzi´c, I.Kuzle, "The Mixed-Integer Linear Optimization Model of Virtual Power

Plant", 8th Conference on the European Energy Market (EEM), 25-27 May 2011, Zagreb, Croatia.

[23] M. Ceraolo, M. Conte, R. Giglioli, G. Lutzemberger, M. Pasquali, "Use of electrochemical storage in substations to enhance energy and cost efficiency of tramways", AEIT Conference 2013 (IEEE Italy Section), Palermo, Italy, October 3-5, 2013.

[24] D.B.Robinson, "Optimization of power and energy densities in supercapacitors", Journal of Power Sources, Vol. 195 Issue 11, June 2010.

[25] S. Barsali, M. Ceraolo, M. Marracci, B. Tellini, "Frequency Dependent Parameter Model of Supercapacitor", Measurement Vol 43, Issue 10, December 2010, pages 1683-1689 (ISSN 0263-2241).

[26] M. Ceraolo, G. Lutzemberger, M. Marracci: "High power lithium batteries usage in hybrid vehicles", Vehicle Power and Propulsion Conference (VPPC), 2010, IEEE Lille (France) 1-3 Sept. 2010, ISBN 978-1-4244-8220-7.

[27] M. Ceraolo, G. Lutzemberger, M. Funaioli, L. Sani, D. Poli: "Electricity storage to enhance energy and cost efficiency of urban railroad systems", Railways 2014, The Second International Conference on Railway Technology: Research, Development and Maintenance Ajaccio, 8-11 April 2014.

Figure captions

Figure 1: Picture of the inverter and storage containers

Figure 2: Principle scheme of droop control

Figure 3: Grid frequency (green, square marks) and real power (red, circle marks) during operation at 2% frequency droop and power setpoint at -30 kW (battery charging)

Figure 4: Wind turbine, cogenerator and thermal storage, electric storage inverter and PV plant

Figure 5: Structure of the Smart User: connection between thermal and electric devices, including energy storages.

Figure 6: Real and reactive power exchanged with the grid during 50 minute operation (positive real power: uphill, negative real power: downhill)

Figure 7: AC voltage (circles) and current (squares) waveform at the cable car grid side terminals during uphill operation

Figure 8: Renewed system scheme.

Figure 9: Single phase real power (blue: drive power; red: grid demand; green: storage power, positive when storage is discharged).

Figure 10: Voltage (red) and current (blue) waveforms during a downhill trip and the relevant current harmonic spectra. Left: at drive terminals; middle: at compensator terminals; right: grid.

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Table 2: Energy absorbed with regenerative braking as a function of the number of substations equipped with storage

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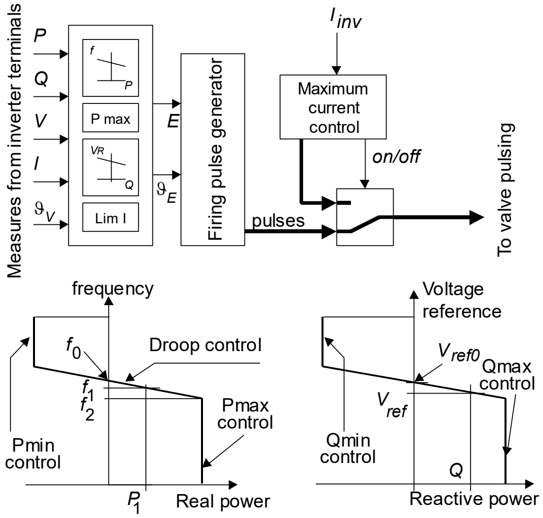

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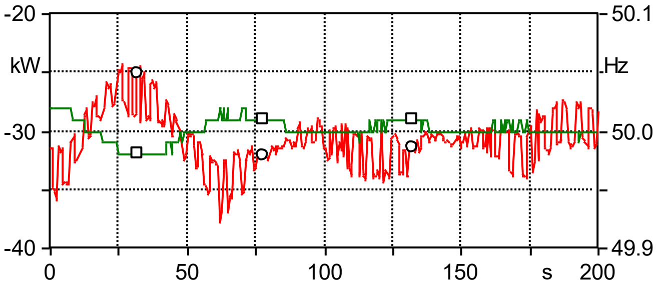

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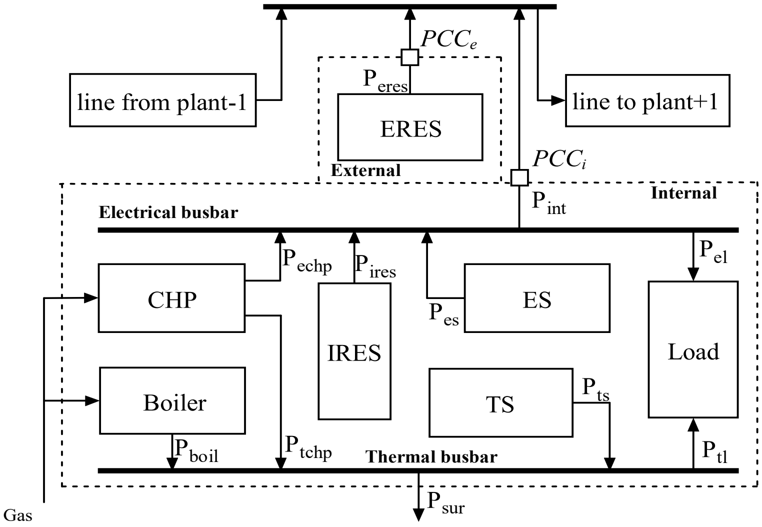

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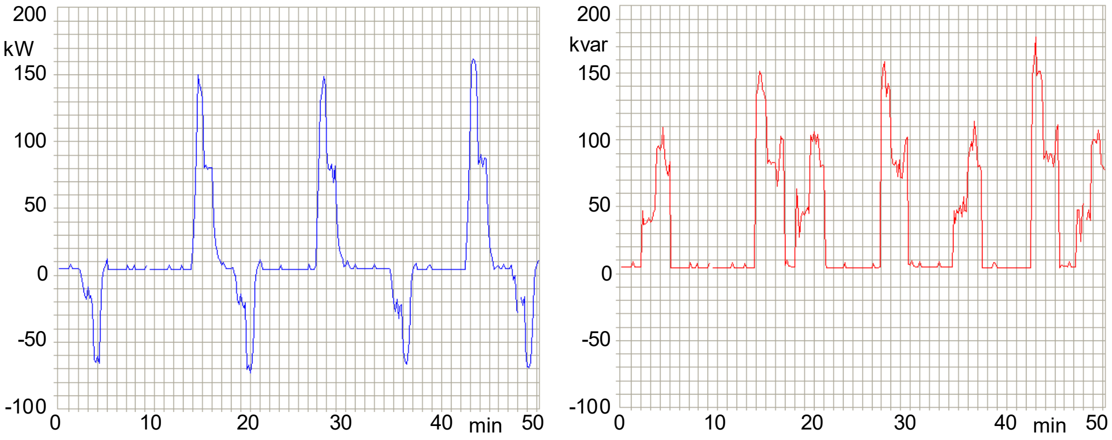

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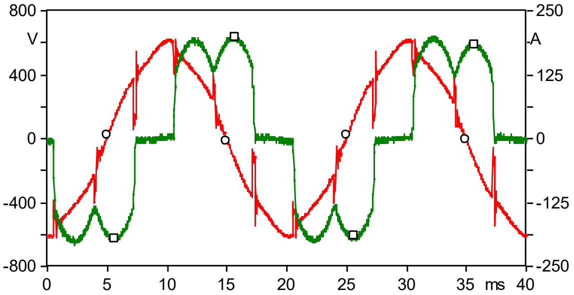

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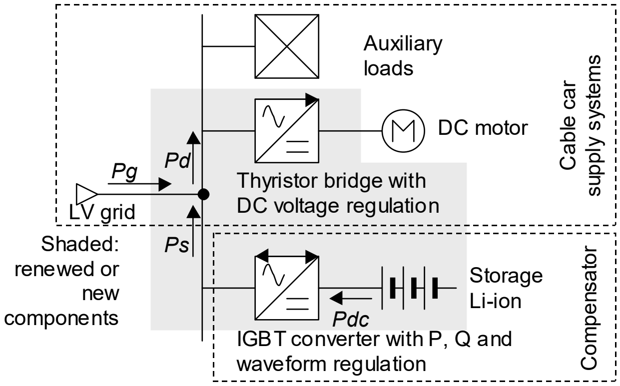

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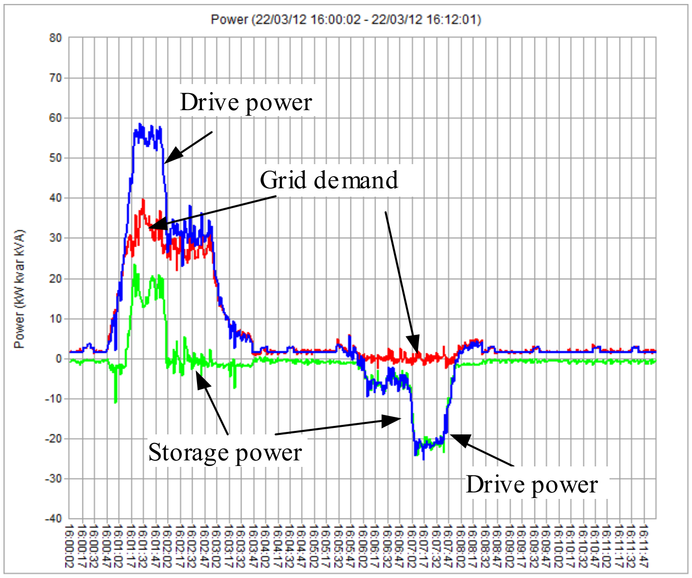

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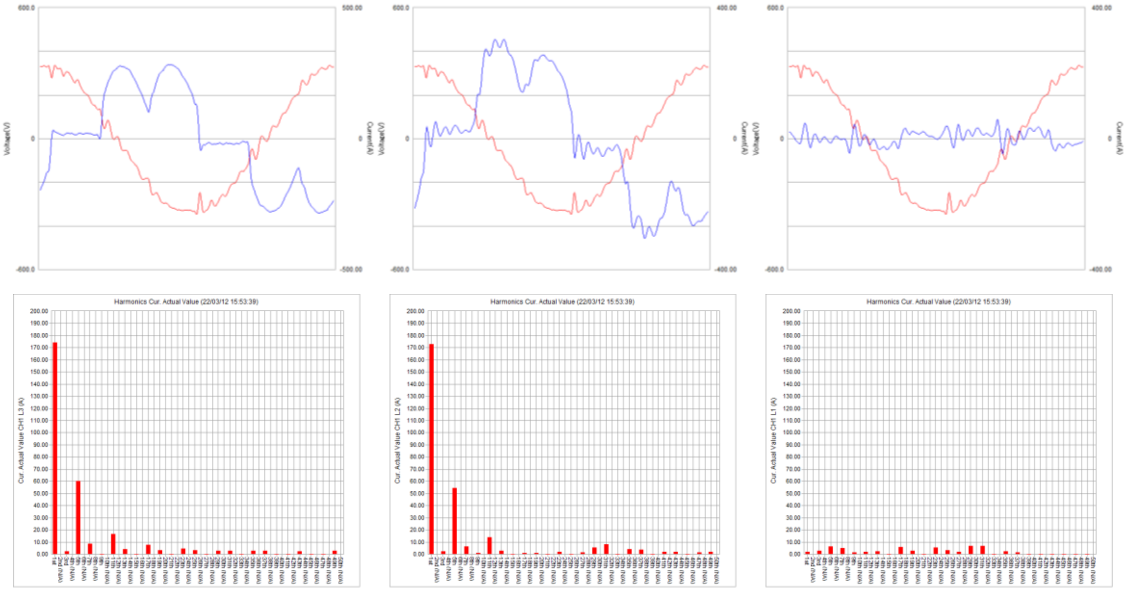

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Tables

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of the economic benefits expected for different services

POWER SERVICES							ENERGY SERVICES			
Security					PQ	Access	Security	PQ	Access	Energy effic.
Peak shaving (generation capacity)	Congestion resolution	Islanding	Ramp	Black Start-up	V regulation, active filter, dip, flicker, microinterr.	Peak shaving (network capacity)	Load leveling Valley filling	Medium and long interruptions	Network capacity (several hours/day)	Primary conversion and transport losses
400 ÷ 600	**50 ÷ 150**	**1000 ÷ 1200**	**600 ÷ 800**	**180 ÷ 200**	**350 ÷ 800**	**250 ÷ 300**	**400 ÷ 600**	**250 ÷ 400**	**250 ÷ 400**	**90 ÷ 120**

Table 2: Yearly energy absorbed with regenerative braking
as a function of the number of substations equipped with storage

storage systems [#]	Energy absorbed [MWh]	Total energy saving [MWh]	Incremental energy saving per storage system [MWh]
0	2869	0	0
1	2612	257	257
2	2397	472	215
3	2049	820	348
4	1820	1049	229
5	1769	1100	51
10	1641	1228	26