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San Severino Marche Smart Grid Pilot within the InteGRIDy project

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Abstract

This paper reports the presentation of a Smart Grid architecture designed with respect to the actual Italian scenario and ongoing to be experimentally validated in the distribution grid of San Severino Marche Pilot, Italy. The main characteristics of the smart grid architecture deployed are discussed and two of its innovative functionalities are detailed: reconfiguration of the Medium Voltage (MV) grid and Energy Storage Systems (ESSs) exploitation for the ancillary services provision. Such functionalities are introduced from both a theoretical and an experimental point of view. Data collected from the field have been processed by means of mathematical models in order to achieve a quantitative evaluation of the performances. Results are related to the energy losses improvement the DSO could obtain thanks to a MV grid reconfiguration and to the economic viability of ancillary services provision by means of distributed ESSs. For the first functionality, an Exhaustive Research, a Genetic Algorithm and a Monte Carlo heuristic procedure have been coded and compared. For the latter functionality, an electric model of an ESS has been exploited in order to simulate a contribution to the primary frequency control and an ancillary market model has been developed in order to evaluate a multi service management of the storage; in particular frequency response and self-consumption logics have been evaluated.

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Keywords: Smart Grids; Energy Storage Systems; grid reconfiguration; Genetic Algorithm, Monte Carlo Optimization, Demand Response

1. Introduction

Renewable Energy Sources (RES) are the main driver of the ongoing energy revolution all over the world. In order to manage RES, electric networks infrastructure and the relevant regulatory/market frameworks need to be

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properly updated. InteGRIDy (www.integridy.eu) is one of the H2020 projects activated by EU commission with the aim of identifying adequate approaches to manage this revolution [1]. Within the InteGRIDy project, ten pilots all over the EU are developed to the test on field the actual performances of new solutions devoted to support the distribution system operation, with respect to four thematic pillars: Demand Response; smartening the distribution grid; energy storage technologies; electric vehicle integration. Actually, these Pilots are addressed to effectively manage the intermittent renewable generation, avoiding costs for grid extension.

The focus of this paper is on the San Severino Pilot, a MV distribution grid sited in the center of Italy, managed by the DSO A.S.S.E.M SpA. [2]. The pilot includesthree of the InteGRIDy pillars: Demand Side Management, Smart Grid andEnergy Storage . In the paper, after a short description of the MV grid under analysis, the smart grid architecture deployed is presented and the main functionalities are described; in particular, a focus is reported on the MV grid reconfiguration and on the exploitation of distributed Energy Storage Systems (ESSs) for the ancillary services provision on the electric market. All the simulations reported in the paper are based on real data measured by the field devices and on price signals collected in the Italian market.

2. San Severino Pilot

San Severino Marche is a small town in the center of Italy, its 20 kV distribution grid has a total length of 180 km, a peak demand of 48.78 MW, and connects 393 generators (27.6 MW). The main typologies of generators are solar and hydro from rivers. Two transformers are placed in the primary substation and five feeders depart from each of them. In the past, the area reported a significant amount of hydro resources while, recently, photovoltaic penetration rises year after year. Moreover, due to the agricultural activities, good opportunities are also related to biomasses. By contrast, the energy needs of loads are quite limited, consequently a reverse power flow (power flowing from the MV grid to the HV grid) regularly occurs, especially during summer time.

Thanks to a past experimental project, the area is already provided with an advanced communication architecture, allowing the exchange of real-time signals/data between the DSO's control center and the users; in particular the communication system is based on fiber optic, Wi-Fi bridges, and mobile network (LTE). Moreover, the Smart Grid core unit is linked to the DSO's SCADA/DMS and to a set of monitoring apparatuses deployed on the grid in primary and secondary substations to properly collect real time measurements about the grid operation [3]. Finally, weather nowcast and forecast equipment are going to be deployed in order to estimate in real time and in advance RES production [4].

Actually, the Smart Grid architecture is designed to provide in perspective advanced services to the DSO:

- forecasting of DERs production on a multiscale time window to provide preventive advices to the DSO;
- real-time and predictive state estimation of the MV network;
- evaluation of the network's performance indexes (energy losses, hosting capacity, etc.);
- identification of the optimal grid topology to be adopted (i.e. which switching devices should be opened or closed, and for how long, to optimize the grid's operation according to given KPIs);
- warnings about possible problems expected on the network in the next future;
- exploitation of ancillary services from the active users equipped with Energy Storage Systems.

The San Severino Marche Pilot is arranged with respect to two different goals: the DSO perspective and the final user perspective (mainly domestic users). The first is related to an improvement of the distribution grid efficiency and quality of supply; such goals drive to economic income to the DSO thanks to an optimal management of the distribution grid. Also the grid's Hosting Capacity (capability to connect new generators) will benefit of the solutions designed in the project, thanks to the minimization of grid congestions obtained by the adoption of energy storage solutions and Demand Response strategies. On the other side, the final user will have economic gain thanks to an effective participation to the Demand Response logics, providing services to the local grid or to the ancillary market. These functions are nowadays under evaluation in the Italian system: the regulatory framework is not yet completely defined, consequently the project results particularly on-time in order to provide useful on field results. Eventually, thanks to the ESS apparatuses, the active users will be able to better manage the energy needs in the houses (increasing the self-consumption), minimizing the energy bill.

In particular, in the first step of the project the focus has been devoted to two main functionalities:

- to manage the topology of the MV grid (by delivering suitable information to the DSO, in real time and in advance) in order to improve its operational efficiency (e.g., reducing energy losses, maximizing the grid's hosting capacity for RES);
- to collect ancillary services (frequency regulation, congestions mitigation, etc.) on active and passive users, by means of Energy Storage Systems.

In the following of the paper, each functionality is described detailing the field activities, the lab tests and the numerical simulations.

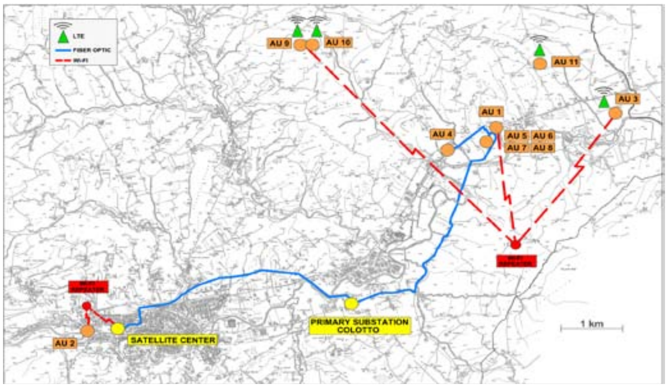

Fig. 1. Communication infrastructure and Smart ICT infrastructure deployed in the pilot.

3. Network reconfiguration

In this work, we developed and compared different strategies aimed to optimize the configuration of a MV distribution network assuming as objective function the minimization of energy losses on grid's conductors and transformers. The final purpose of the work is to develop a mathematical approach to be deployed within the InteGRIDy project as software tool. The conceived tool will provide to the DSO in real-time and in advance useful suggestions about the grid configuration that, according to the load and production actually measured or forecasted on the grid, will optimize the grid's efficiency. The optimal approach must ensure the best trade-off between effectiveness of the mathematical solution provided (i.e. closeness to the global optimum of the problem) and computational costs (i.e. processing time) required by the solver to find it. Given the huge number of viable configurations for a real MV distribution network, the method must primarily be effective in managing in a reasonable time the complexity of the mathematical problem. In this framework, a quasi-optimal solution is usually considered acceptable in order to limit the computational time.

In our analysis, in particular, we considered three different optimization strategies:

- a method based on the Exhaustive Research (ER), processing all possible configurations to find the global optimum of the problem [5];
- a Genetic Algorithm (GA), defining an initial population of candidate configurations that is evolved iteratively [6, 7], by selection, crossover and mutation of individuals, toward the best solution;
- a Monte Carlo (MC) algorithm, selecting the network configurations to be adopted by a probabilistic approach assigning proper weights to each grid solution according to its closeness to a reference configuration.

The ER algorithm has been developed to have a benchmark for both the identification of the optimal solution and the computational effort required. GA is a well-known technique here adopted looking for a reduction in the computational effort, even accepting a limited degradation in the optimal solution identification. MC is another well-known approach; in this paper, a custom algorithm has been developed with the goal to take into account some practical bounds the DSO have to manage in real life operation of the distribution grid. Actually, a limited number of control actions are allowed; such a bound is supposed to limit the probability of loss of supply events caused by faults in the automation equipment; moreover, if properly coded, it results quite effective in driving a strong reduction of the computational effort (see section 3.3 and 3.4).

In the following, each optimization strategy is presented; then, they are tested and benchmarked on the real MV grid of San Severino Marche, obtaining useful indications for their future implementation in the InteGRIDy project.

3.1. The Exhaustive Research method

The Exhaustive Research (ER) method is based on a preliminary analysis of the network structure to identify the set of configurations considered admissible from a merely topological point of view: i.e. grid's configurations allowing all users to be supplied by the main grid (absence of electric islands) and not showing electrical loops (in accordance with the hypothesis of network operated as a radial system). Then, the method evaluates by power flow calculations, for each network configuration considered admissible, the relevant energy losses occurring on conductors and transformers. This is usually a computationally intensive operation, because a power flow calculation is needed for each sample of power profiles (e.g. every hour of the year) and each admissible configuration. Finally, the optimal solution is selected as the configuration able to ensure on the period under analysis the lowest energy losses. Given its ability to always find the global optimum of the problem, in this study the ER is used as reference term to measure the performance of the other developed strategies.

3.2. Genetic Algorithm approach

The use of a Genetic Algorithm (GA) to optimize the network configuration requires to adopt a proper mathematical formulation of the problem, representing the state of each switching device over the network as a binary variable (1 = closed; 0 = open). For this purpose, sectionalizing switches (i.e. devices installed along MV lines, assumed closed in the base case network configuration) will be assigned a value equal to 1, while tie-breakers (i.e. devices installed at the end of MV lines to allow emergency back-feed of electrical lines, assumed open during the standard operation) will be modeled with a value equal to 0.

The solver aims to optimize the following objective function, representing the energy losses estimated on the MV grid over a given period:

$$Min\ f_h = \sum_{i=h+1}^{i=h+T} E_{loss}(X,i)$$

Where:

- h is the hour of the year for which the optimization tool is run;
- $E_{loss}(X,i)$ is the total amount of energy losses, evaluated through power flow computations, function of the configuration X and hour of the year i considered;
- T is the time horizon (in hours) on which the losses forecasting and network optimization is performed (e.g. for a weekly optimization, $T = 168$).

The Genetic Algorithm is implemented by using the Mathworks Matlab Optimization Toolbox. During the evolutionary process, the combinatory generation of new grids is bound only to topological admissible configurations (i.e. without electrical loops or islands); to this aim, suitable inequality constraints have been introduced in the problem, for example to exclude the simultaneous opening or closing of given switching devices.

3.3. The Monte Carlo approach

The Monte Carlo approach developed within the InteGRIDy project aims to the optimization of the configuration of the MV network of San Severino Marche on the basis of estimated energy losses. To this goal, as first step, the proposed approach provides to assign to each feasible network configuration a proper weighting coefficient. The coefficient is determined according to the closeness of the selected configuration to the base case, in terms of number of switching maneuvers required to pass from the base configuration to the selected one: i.e. among all the possible grid configurations investigated through the Monte Carlo algorithm, a greater probability is assigned to those more similar to the configuration previously selected as optimal. This strategy is based on the assumption that in real-life scenarios, during normal operation (i.e. when the network functioning is only affected by load/generation daily/seasonal fluctuations), the changes required to rearrange the network are usually limited (e.g. passing a few users from a MV feeder to the adjacent one). Moreover, during the year, it is pivotal for the DSO to limit the number of switching maneuvers required for the reconfiguration process, since a greater number of maneuvers means higher costs for the maintenance (and eventually substitution) of the switching devices. Therefore, again, a higher priority of grid configurations near the base case is convenient.

In the approach proposed, first of all, for every feasible configuration (no loops or electric islands) the number of maneuvers required for the grid rearrangement is determined. Then, for the *i-th* configuration, the corresponding weight is computed as:

$$w_i = \frac{SW_{max}}{SW_{ib}}$$

Where:

- SW_{ib} is the number of switching maneuvers to move from the base case configuration to the *i-th* one;
- SW_{max} is the maximum number of switching maneuvers required to move from the base case to all other possible configurations.

During the running of the Monte Carlo tool, grid configurations are randomly chosen considering the corresponding weighting factor. For each configuration, a set of power flow calculations is performed, estimating the energy losses occurring on the grid on a given time interval. The process keeps on going until a convergence criterion specifically developed is met. In particular, the criterion relies on the fact that, for a normally distributed random variable x, with mean $\bar{x}$ and standard deviation S_x, a confidence level and an interval can be defined that are function of the number of samples n. For example, if a confidence level of 90% is selected, then it can be stated with 90% of confidence that the true mean will exist between the interval L and U given as:

$$(L, U)_{0,90} = \bar{x} \pm 1.645 \frac{S_x}{\sqrt{n}}$$

3.4. Network reconfiguration: numerical results

The analyses have been conducted on the model of the real distribution network operated by A.S.SE.M. S.p.A., depicted in Fig. 2 [8]. As already mentioned, it has a radial structure, starting from an HV/MV primary substation equipped with two 10 MVA transformers; the MV busbars underlying the transformers operate separately. For sake of simplicity, the paper will refer only to the part of the network departing from one MV primary busbar, having 4 feeders and an overall of 287 buses, representing the HV and MV busbars of primary substation (2 buses), the MV users (10), the MV/LV substations (109) and points of interconnection between different line conductors (166). Because of the complexity and spreading of LV networks, only the MV level is modeled in detail. Therefore, the loads are classified in two different categories, MV users and MV/LV substations (LV loads are introduced in the model as equivalent power exchanges at the MV/LV interface). Moreover, DG power plants deployed on the distribution network are also modeled. Users' power profiles are represented on an hourly basis over a whole year (8760 hours). All passive users in the same category are modeled with the same absorption profile obtained from the yearly characteristic of the overall Italian national load and are assumed absorbing energy with a power factor equal to 0.9 lagging. Finally, each generator is assigned a proper injection profile with a unitary power factor.

Fig 2. shows, respectively as red and blue dots, the sectionalizing and tie-switches on the network. For tie-switches, two blue dots equally numbered identify the terminals of each device, which allows two buses of the grid to be electrically interconnected in case of need. This represents the base case configuration, that is used as benchmark to test the performances of the optimization methods, as illustrated in the following.

In the GA approach, respectively, unitary and null values are assigned to chromosomes relevant to sectionalizing switches (a÷i, red letters in the figure) and tie-breakers (1÷7, blue numbers in figure). Moreover, the following parameters have been found as a suitable compromise in GA between accuracy of selection of the best configuration and computational burden of the process:

- Population Size = 350
- Max Generations = 5
- Max Stall Generations = 3
- Crossover Fraction = 0.5
- Elite Count = 2

In order to the test the effectiveness of the strategies developed in optimizing the behavior of the San Severino Marche MV network, we performed suitable numerical simulations aiming at comparing the performance achievable with the different approaches, in terms of reduction of energy losses with respect to the base case scenario. Moreover, the computational effort required to solve the mathematical problem has been considered as another key aspect for the comparison, because, in large networks, or in highly meshed ones (e.g. covering urban areas), the number of switching devices to be managed could cause an unaffordable increase of the time required to perform the necessary calculations.

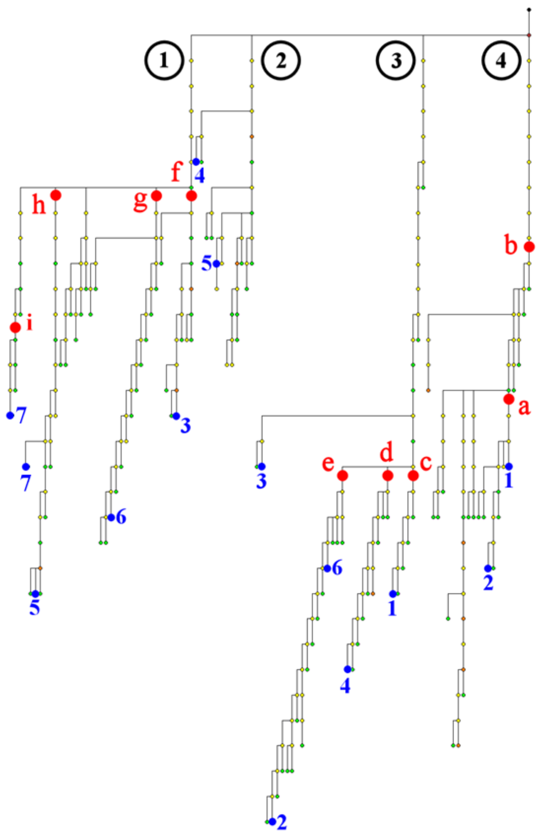

Fig. 2. The MV network model adopted. The sectionalizing switches are reported as red dots, while the tie-switches are in blue.

In detail, the numerical results have been obtained by simulating the behavior of the network during about three months (13 weeks) in the period 1st January 2014 – 1st April 2014. The reconfiguration tool is assumed to run once a week to identify the optimal configuration that, according to the power flows forecasted on the grid, is able to minimize the overall energy lost on power lines in the next 7 days.

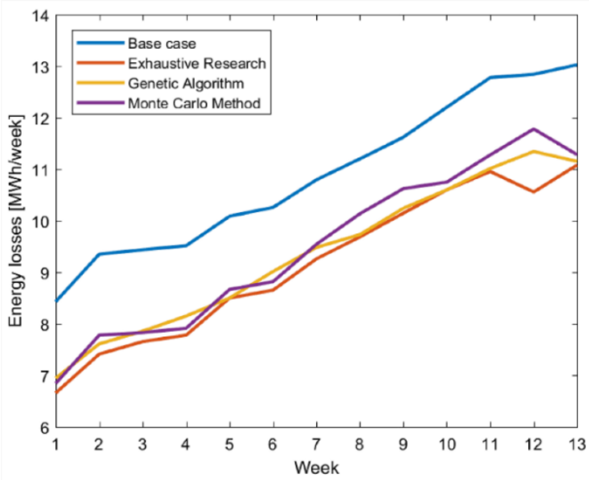

Fig. 3. Weekly energy losses on the MV network in the base case (without optimization) and with the optimization strategies developed.

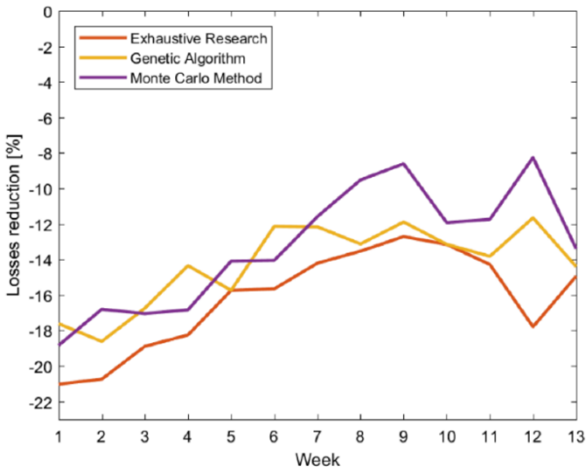

Fig. 4. Reduction of weekly energy losses estimated on the MV network with the optimization strategies developed w.r.t. the base case.

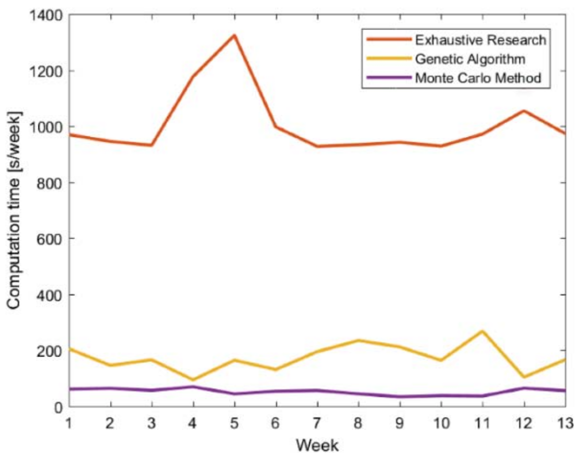

Fig. 5. Computation time [s] required to run each optimization strategy over one week.

Fig. 3 reports the energy losses estimated on the network in each week of the period under analysis assuming to operate its reconfiguration according to the suggestions of each optimization method. The results are benchmarked against the energy losses occurring in the base case configuration (i.e. the configuration adopted statically by the DSO in real-life). One can observe that all the optimization strategies proposed allow for a significant losses reduction with respect to the initial scenario. The ER method, as expected, always identifies the global optimal grid configuration, i.e. the one able to minimize (in a strict mathematical sense of the term) the energy losses. On the other hand, GA and MC methods show both lower performances, allowing for a smaller improvement of the power distribution efficiency if compared to ER.

As highlighted in Fig. 4, depicting the energy losses reduction in percentage w.r.t. the base case, the ER is always the method best performing, but GA and MC also show more than satisfying results: a reduction of energy losses between 9 and 19% is achieved in every week of the period under study, falling behind the exhaustive research of only about 2% (on average, 1.96% for GA and 2.94% for MC).

Finally, Fig. 5 shows the time required to perform each weekly computation with the three optimization methods proposed. The extent of time reduction obtained by GA and MC approaches fully motivates, in practical applications, the lower accuracy in identifying the optimal solution: while the ER requires on average about 16÷17 minutes to perform a weekly optimization, the GA only needs 2’52’’ and the MC just 52’’. Even if in the case study under analysis (tool run once a week on a grid with 16 switching devices) the computation times of all the three methods developed proved to be widely compliant with the practical use, we stress that the optimization strategies have to be designed to manage also situations of greater complexity, both in terms of grid structure and number of switches to control; such situations can be considered quite common in the Italian scenario.

4. ESSs for ancillary service provision

The second functionality implemented and tested within the research activity is the aggregation of ESSs deployed in the distribution grid under evaluation; the final purpose is the multi services management of ESSs. Actually, ESSs have been coupled to active users, to maximize the self-consumption of the locally generated energy, and to provide ancillary services for the grid. In particular, a fraction of the ESSs power (and energy) capability has been reserved for the ancillary service provision with the goal to improve the users economics.

In order to test components and strategies that will be adopted in San Severino Marche Pilot, laboratory activities have been carried out in the Internet of Things lab of Politecnico di Milano [9]. Data, related to grid parameters (mainly frequency and voltage) sampled in the lab have been exploited to set up numerical simulations effective in the evaluation of the contribution of active and passive customers to the ancillary service market by means of an aggregator, that is assumed to be coordinated with the DSO.

4.1. Lab activities

A first step toward the simulation of the ESS ancillary services provision has been the definition of a frequency profile representative of the standard working conditions of the Italian power system. The definition of a standard profile is fundamental because the actual frequency profile will affect the duration and the magnitude of the energy exchanges required to the ESS. For such a goal, within the Internet of Thing lab of Politecnico di Milano, frequency samples have been acquired and elaborated with a National Instrument Compact Rio unit. This system is able to elaborate measurements and compute control actions to be performed locally, but also to share data and commands through the cloud. The signals of interest have been acquired with a sampling frequency of 10 Hz for 33 consecutive days, in the period between 15th February and 19th March 2017.

The sampled daily frequency profile is shown in Fig. 6 in terms of average value and standard deviation for each instant of time. Common patterns are visible across the days; such patterns have been identified in a rigorous way adopting a frequency-domain characterization of the time series. To do this, the frequency profile of each day has been analyzed with the Fast Fourier Transform. The amplitude of the harmonics for each measured day is shown in Fig. 7 in form of boxplots: the first harmonic corresponds to the slowest variation (12 hours) and, reading the graph from left to right, faster variations are considered. The harmonics around the 24th correspond to hourly trends that are clearly related to the schedule of the Italian day-ahead electricity market (hourly based). Other trends appear related the harmonics close to the 48th and the 96th (half-hour and quarter-hour variations); also these trends are related to the electricity market, specifically to the ancillary service market (quarter-hour based). Such a quantitative approach is devoted to develop a synthetic frequency signal that preserves the highlighted characteristic of the measured frequency.

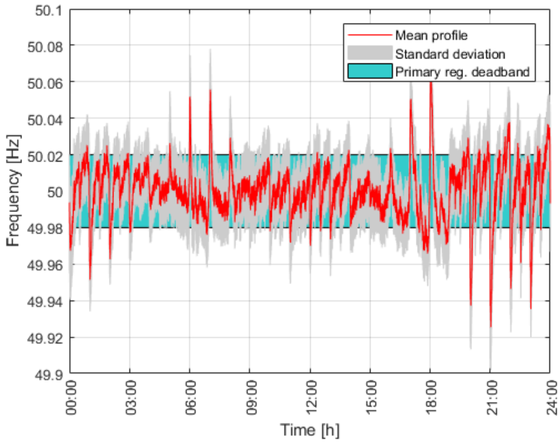

Fig. 6. Figure on frequency samples collected in the IoT lab

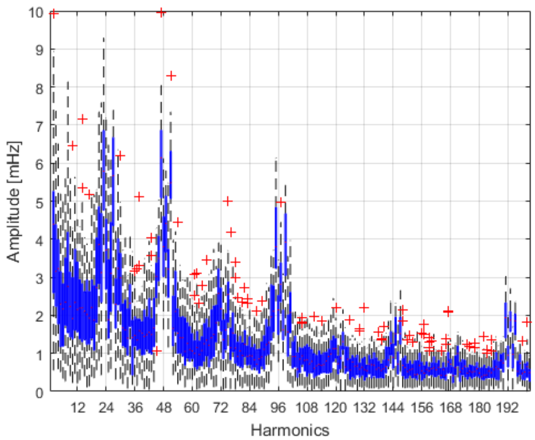

Fig. 7. Fourier decomposition of the frequency profile collected in the IoT lab

Given the frequency sampled collected in the lab over 33 days, data have been evaluated and a 7 consecutive days profile has been extracted, excluding abnormal samples/trends in the frequency. Such samples have been injected in a standard primary frequency controller set with respect to parameters correspondent to the Italian Grid Code (20 mHz DeadBand, 5% droop). Consequently, samples of primary frequency response (power [MW]) have been obtained. Such set points have been applied to an ESS model in order to simulate charge/discharge processes inside the battery, consequently a proper ESS mathematical model has been developed.

Different kinds of battery models have been proposed in literature to emulate the behavior of the internal electrochemical processes, with different degrees of complexity. Regardless the complexity of the model, two main factors have been taken into account: modeling of operating condition (i.e. SoC estimation) and modeling of aging (i.e. SoH estimation). In particular, in this work a model based on the electrical properties of a battery has been adopted. The utilization of this model allows to monitor current fluctuations, voltage and efficiency of the battery depending on the different utilization (i.e. power setpoint imposed). The model adopted, related to Lithium-ion cells, is detailed in [13]. It links the electrochemical equations that govern the internal processes to the equivalent modeled impedance. The SoC estimation given by the model can be used to assess the effectiveness of the battery for its final application. Overall, the model is described by nine independent parameters, derived by EIS (Electrochemical

Impedance Spectroscopy) and OCV (Open Circuit Voltage) measurements [10, 11]. In practice, the model consists of an incremental capacitance look-up table and eight RC parameters which are dependent on the OCV.

The parameters utilized in this work have been collected at the Energy Storage Research Center (ESReC) located in Nidau (CH). The measurements were carried out within the framework of the collaboration between Politecnico di Milano (Department of Energy) and CSEM-PV Center (Swiss Center for Electronics and Microtechnology). The experimental tests refer to LNCO cell (Li-ion) of Boston Power (model SWING5300) [12]. This work utilizes the results about efficiency tests, OCV tests, EIS tests and aging tests (details are given in [11,12]). The Li-ion cell model presented above is utilized in the battery block; note that, in this approach, the ESS configuration is scaled down to cell level by neglecting all those modeling steps that are proper of the battery pack level like the BMS cells' balancing and equalization. Nevertheless, a simplified BMS is implemented to prevent any current supply or absorption when the cell voltage reaches its limits [13]. Solving the model exploiting the Matlab package, the ESS provision of the primary frequency control has been simulated [14]. Data related to the battery behavior has been collected: Open Circuit Voltage-VOC, C-rate, State of Charge – SoC, Loss of regulation (i.e. interruption of the service due to SoC saturation) and, finally, the power profile (in p.u.) at the ESS terminals.

4.2. Preliminary economic evaluation of the multi-service ESS

As already introduced, in a cost effective smart grid vision, it is important to evaluate the impact of ESS exploitation not only for increasing self-consumption, but also for guaranteeing the provision of some ancillary services, on the economics of the storage itself. Given a user provided with a PV generation, in a BAU (Business As Usual) situation, due to a lack of contemporaneity between PV production and load request, the amount of energy self-consumed has been evaluated equal to 61% of the energy produced. This is visible in Fig.8, looking at the red (PV) and green (load) profile, which are taken from real measurements of an active user involved in the San Severino pilot (one week).

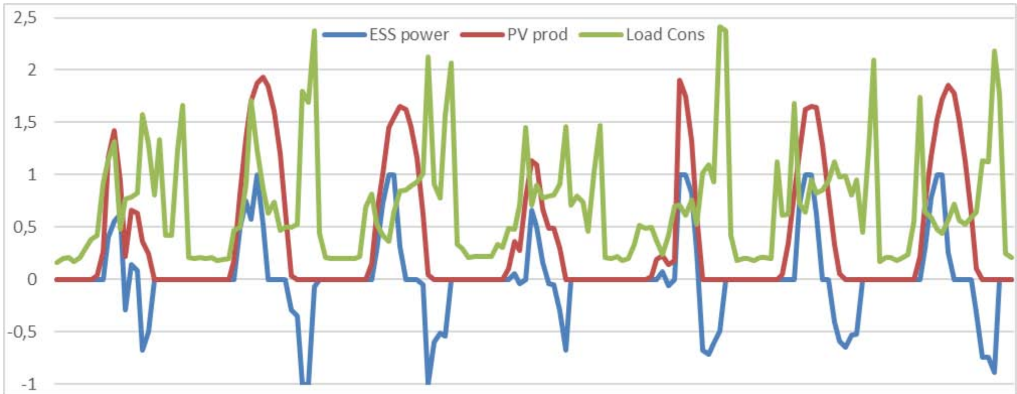

Fig. 8. Simulated power flows [kW] for the ESS coupled with a PV power plant over a 7 days time window (self-consumption logic)

Taking into consideration that self-consumption of energy guarantees a money saving such as 0.12 €/kWh (determined as the difference between cost of energy in the bill, 0.18 €/kWh, and average value paid for injected energy, 0.06 €/kWh) the possibility to consume directly in place the energy produced by the PV plant introduces a saving of about 285 € per year, due to the natural coincidence of production (red) and consumption (green) profiles. The exploitation of an ESS, sized at 1 kW/3 kWh (a reference design of ESS in domestic application in the Italian scenario) could increase self-consumption, and improve the economic performance. In the simulation performed, if the ESS is entirely devoted to maximize self-consumption, the percentage of PV production which is in the end consumed locally increases up to 86%, guaranteeing a money saving of about 402 € per year.

As shown in Fig.8, the ESS follows the evolution of PV and load profiles, encountering rarely some constraints on its power limit, however reaching more often SoC saturation, with a consequent impossibility to operate further. Starting from this scenario, the possibility of performing network services with the same ESS has been investigated.

In particular, a percentage of the ESS nominal power is reserved for providing ancillary services. Given the characteristics of ESS, two ancillary services have been considered together: Frequency Containment Reserve (FCR, also known as Primary Reserve) and Frequency Restoration Reserve (FRR, also known as Secondary Reserve). This kind of services are typically fast response, quasi continuous services which can better fit with the principal service provided by the ESS under analysis. Detailed models have been exploited for simulating the two services. In particular, FCR energy exchanges are calculated by the model described in section 4.1. As for FRR, the relevant activation, and consequent energy exchanges, are calculated on the basis of the secondary reserve activation signal (so called "level signal"), that is issued by TERNA (the Italian TSO) for each zone of the system.

For the simulation, taking into consideration the requirements currently in place for conventional resources (1.5% for FCR; 6% for FRR) for which the ratio between the Secondary and Primary band is 4:1, a reservation of 40% of nominal power to provide Secondary Reserve, and of 10% of nominal power to provide Primary Reserve, has been considered. The simulation carried out considered the advantage of having three distinct modes of operation (self-consumption, FCR and FRR) integrated in the same device. In Fig. 9 it is possible to see the same quantities presented above in this second configuration, where the ESS power devoted to self-consumption is now halved.

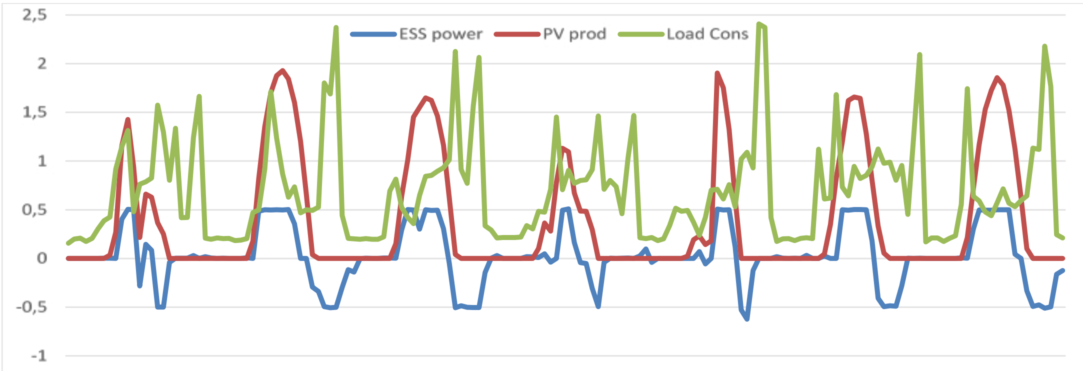

Fig. 9. Simulated power flows [kW] for the ESS coupled with a PV power plant over a 7 days time window (multi service logic)

The self-consumption management is now characterized by more relaxed charging and recharging trends. Power peaks provided by ESS are reduced, since a share of the nominal power has been devoted to other services, but charging and discharging cycles have a wider duration. Notably, the reduction of ESS power available for self-consumption does not influence significantly the relevant economic benefit. Apart from the power band reservation (always present), ESS is exploited for FCR & FRR only in a reduced share of time, since the relevant signals are not always active. The remuneration of both frequency services has been calculated according to market rules currently adopted in Italy: in in case of activation, a constant value for FCR, and an hourly value for FRR (as determined by the ancillary services market results, publicly available in [15]). On top of this, a capacity premium has been added, in accordance with upcoming EU regulations on the subject [16].

As a result of the preliminary analysis performed, the percentage of self-consumed energy over total energy produced is around 83%, in the case of ESS with multiple services taking half of the power. This leads to a saving of 388 € per year, with a loss induced by the band reservation of 14 € (402 € - 388 €). In change of this, the provision of ancillary services (adopting just a fraction of the ESS capabilities) is estimated to bring two different revenue streams:

- around 15 € per year, considering a capacity premium payment of 30 €/kW/year for frequency services;
- around 13 € per year, considering the energy remunerations from the actual provision of FCR and FRR.

5. Conclusions

This paper presents the first results obtained, within the InteGRIDy project framework, in an experimental Smart Grid deployed in the distribution system of San Severino Marche, a ton located in central Italy. The first functionalities activated and tested are related to the optimization of the MV grid topology and to the exploitation of distributed ESS for ancillary services provision.

For the first functionality, a state estimation function has been exploited in order to define a mathematical model of the grid, with power flows sampled since 2014; such information has been exploited in a new procedure devoted to optimize the topology of the MV grid with respect to active power losses. Actually, several optimization techniques have been coded and compared: Exhaustive Research, Genetic Algorithm and Monte Carlo algorithm. Numerical results pointed out good performances improvement achievable thanks to the procedure developed (i.e. the losses minimization results solid, up to 20% with respect to the base case scenario); with respect to the mathematical formulation of the problem, GA and Monte Carlo techniques proved to be effective in managing the optimization problem limiting its computational effort.

The second functionality is relevant to active users provided with a PV power plant and with an ESS. ESSs have been designed in order to maximize the users' self-consumption and, in an experimental perspective, also to provide ancillary services to the main grid. Ancillary services revenues have been estimated and the economic viability of the proposed ESS multi services logic has been evaluated. Users' self-consumption, primary frequency regulation and secondary frequency regulation have been simulated as joint services. Results obtained from numerical simulations are promising: setting a fraction of the ESS power capability for the provision of ancillary service causes a limited reduction in the self-consumption performances, while allows interesting economic benefits to the final user.

The numerical validation of both the functionalities investigated resulted positive; consequently, the next step of the InteGRIDy project will be the activation of the algorithms in the field equipment.

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