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A novel integrated real-time simulation platform for assessing photovoltaic penetration impacts in smart grids

Lorenzo Bottaccioli[a], Abouzar Estebsari[b], Edoardo Patti[a], Enrico Pons[b,*], Andrea Acquaviva[a]

[a]Department of Control and Computer Engineering, Politecnico di Torino, C.so Duca degli Abruzzi, 24, Torino 10129, Italy
[b]Department of Energy, Politecnico di Torino, C.so Duca degli Abruzzi, 24, Torino 10129, Italy

Abstract

For future planning and development of smart grids, it is important to evaluate the impacts of PV distributed generation, especially in densely populated urban areas. In this paper we present an integrated platform, constituted by two main components: a PV simulator and a real-time distribution network simulator. The first simulates real-sky solar radiation of rooftops and estimates the PV energy production; the second simulates the behaviour of the network when generation and consumption are provided at the different buses. The platform is tested on a case study based on real data for a district of the city of Turin, Italy.

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Keywords: Distributed Infrastructure; GIS; Real-Time simulation;PV penetration; PV system; Smart Grid

1. Introduction

Many countries, especially following the Kyoto protocol, are fostering the connection to electricity networks of low-carbon and sustainable generation technologies, in particular photovoltaic (PV) systems. In this framework, an interesting opportunity is the conversion of passive buildings rooftops into active PV rooftops, in order to exploit the available surfaces without subtracting additional portions of land from other uses.

It is difficult to estimate the generation capacity from PV that will be installed in the future years to distribution networks, especially in urban areas. Furthermore, the Distributed Generation (DG) placement will not necessarily follow an optimized planning strategy. For these reasons the analysis of possible future scenarios is really important for different stakeholders, such as Distribution System Operators (DSOs), Energy and city planners, policy makers, etc. Increasing penetration levels of PV require robust tools that help assess the capabilities and requirements of the networks [1,2].

In the estimation of renewable potential Geographic Information Systems (GIS) tools have been largely used as reported in [3]. Freitas et al. report how GIS tools have been applied for solar energy applications in urban contexts [4].

* Corresponding author. Tel.: +39 011 090 7134 ; fax: +39 011 090 7199.
E-mail address: enrico.pons@polito.it

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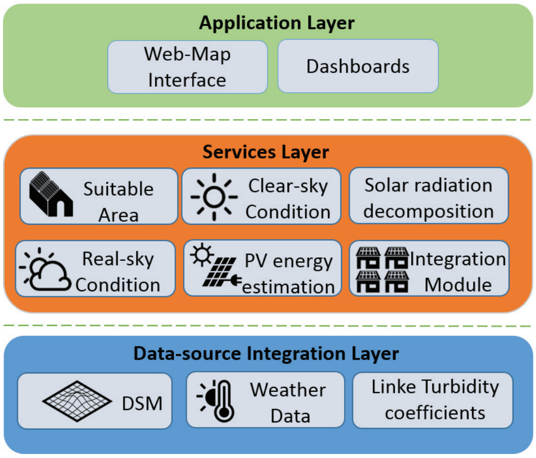


Fig. 1. Scheme of the software architecture for PV systems integration into Smart Grids

Camargo et al. highlight that the major limitation of current GIS tools consists on neglecting time domain [5]. This is reflected even in web-based platforms for photovoltaic potential analysis such as [6–9] that neglect time-dependent simulations. In addition, such services do not take into account electricity consumption and network topology, which is relevant to estimate realistic integration of PV systems into the grid.

In the research field of PV potential estimation, new procedures that consider both spatial and temporal domains are recently emerging [5,10,11]. These works have paved the way to spatio-temporal analysis in the assessment of PV potential. Spatio-temporal analysis gives the possibility to assess PV potential by considering the penetration of PV systems into the grid by analysing the integration of consumption and generation profiles. For example, Camargo et al. focus on the necessity to integrate simulated PV production with electricity consumption data for a correct PV integration to avoid network congestions [5].

In the methodology the authors propose, a PV simulator is coupled with a real-time grid simulator, in order to be able not only to consider consumption data and network topology, but also to take into account the electric behaviour of the distribution system.

There are a lot of examples on the applications of real-time simulation to electrical systems including grids, power electronics and control systems. There are two main types of simulations: electromagnetic transient and phasor simulations; however, there are some examples on the combination of them. The most common commercial application of real-time simulation is in the prototyping stage of manufacturing a device or developing a system. This capability of real-time simulation provides the possibility of testing even when there are no physical prototypes [12–14]. Real-time simulation is also widely used before and after prototyping as design and test phases respectively. For example in photovoltaic generation [15] and wind conversion systems [16,17].

The solution presented in this paper is devoted to satisfy the needs of different stakeholders: *i)* ***Energy Communities*** can use it to plan large PV system deployments and perform feasibility studies as proposed in our previous research [18]; *ii)* ***Distribution system operators*** can simulate new control strategies for network balancing and plan retrofits and/or extensions of the existing distribution grid; *iii)* ***Energy and City planners*** can evaluate the impacts of large PV systems installations or monitor the performance of existing ones.

In the following sections the software architecture is presented, with a detailed description of the different modules. The proposed methodology and software architecture is then applied to a district of the city of Turin, Italy, as a case study.

2. Software architecture for planning PV systems integration into Smart Grids

In this Section, we describe our proposed solution for planning PV systems deployment in a Smart Grid environment and evaluating its impact in the distribution network. As shown in Fig. 1, the distributed software infrastructure consists of three layers: i) *Data-source Integration layer*, ii) *Services Layer* and iii) *Application Layer*. Each layer is described in detail in the following. It is worth noting that we simulate the behaviour of a smart grid through a real-time grid simulator integrated in our architecture.

2.1. Photovoltaic system simulator

Fig. 1 represents the scheme of the software architecture to simulate solar irradiance and PV system behaviour considering real-sky conditions in a *Smart City* environment. It simulates sub-hourly real-sky solar irradiance on rooftops in a given area of the city and provides an estimation of PV systems energy production. It has been designed following both microservice [19] and REST [20] approaches to increase software maintenance and to allow integration also with third-party software.

The *Data-source Integration Layer*, the lower one, integrates into the infrastructure the following heterogeneous data-sources: the *i) Digital Surface Model* (DSM), which is a raster image that represents terrain elevation considering the presence of manufactures; the *ii) Linke Turbidity coefficients* that express the attenuation of solar radiation related to air pollution; the *iii) Weather Data* that are information on climatic conditions (e.g. solar irradiance, air temperature and wind speed) provided by third-party services.

The core of our infrastructure is the *Services Layer*:

- *Suitable Area* module exploits *GRASS-GIS* [21] to identify suitable real rooftop surfaces for deploying PV arrays, for instance, excluding dormers and chimneys. It starts its computation from the DSM.
- *Clear-Sky condition* module produces a set of maps with the incident solar radiation for every 15 min in the area of interest, again exploiting *GRASS-GIS* [21]. It also uses as input the monthly *Linke Turbidity Coefficients*. It is worth noting that we selected *GRASS-GIS* because it embeds the *r.sun* tool, which provides an accurate simulation of solar radiation in urban contexts [4,22].
- *Solar radiation decomposition* module provides a set of solar decomposition models present in the literature to calculate both direct normal radiation (DNI) and diffuse horizontal radiation (DHI) starting from global horizontal solar radiation (GHI) retrieved by third-party weather services.
- *Real-sky condition* module calculates the clear-sky index for the DNI and DHI components of solar radiation that can be retrieved by third-party weather services or by the *Solar radiation decomposition* module. Then, it multiplies each clear-sky condition map by such clear-sky index. The result is a set of real-sky condition maps for the area of interest.
- *PV energy estimation* module estimates the size of the deployable PV system and its production based on weather data (i.e. air temperature), real-sky condition and suitable area maps.
- *Integration Module* integrates and correlates information coming from the Smart Grid (e.g. energy consumptions) with the estimated PV energy production data for the same geographic area. As described in Section 2.3, it is a software module to enable the communication with the real-time grid simulator (see Section 2.2). It is worth noting that this module has been designed to integrate also other software platforms for collecting real-time data from the Smart Grid, such as the platforms reported in [23,24].

Finally, the *Application Layer* is devoted to user applications, such as *Web-Map interface* and *Dashboards*, to provide information about performed simulations across the city.

2.2. Real-time grid simulator

Real time simulation is a highly reliable method based on electromagnetic transient simulation which serves a platform to test new control strategies or technologies on a virtual environment emulating the real world system. It provides very trustable real-like information on impacts and benefits of new strategies or devices, which could support decision makings from real time operation and control phase to long-term planning. The possibility of ex-ante tests reduces costs, and enables more complete and continuous testing of the entire system without interruption. Many possible configurations without physical modification can be also tested safely under possibly dangerous conditions.

Real time simulation is actually reproducing the behaviour of a physical system (e.g. electrical distribution grid) through running its computer-based model at the same rate as actual clock time. In other words, in real time simulation,

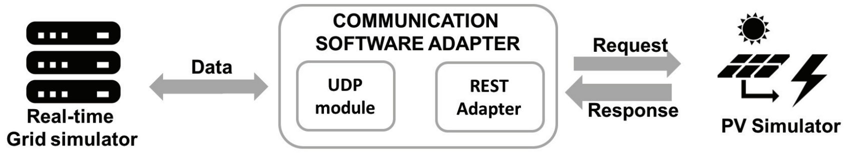


Fig. 2. Integration of PV and Real-Time grid simulators

when the simulation clock reaches a certain time (e.g. 1 s), the same amount of time (1 s) has passed in the real world. It is typically used for high-speed simulations, closed-loop testing of protection and control equipment, and generally all *what-if* analyses. Real time simulation is actually simulating a system, which could realistically respond to its environment, when the inputs/outputs of the simulation are synchronous with the real world.

Considering the advantages of real time simulation, there is a variety of applications to different domains as electricity systems, mechatronics, robotics and industrial automation, automotive application, aerospace, all-electric ships and electric train networks, operator and technician training, electric drive and motor development and testing, and power systems. Among all mentioned fields, power system is the main application domain of real time simulation, using standard hardware-software configuration given by simulator providers. There are two main RTS system providers: RTDS®and Opal-RT®: RTDS products are mainly for power system simulations, and about 80 % of Opal-RT simulators are used for power system applications.

Regarding electricity systems, real time simulation is being widely used in protection and control system development and testing, distributed generation modelling especially renewable energy source (RES) integration (e.g. PV generation penetration), and intelligent grids development.

The purpose of using real time simulator in our work is to model a realistic distribution network to support investigations in terms of PV power penetration impacts in real-world situations. The objective is the simulation of the behaviour of prosumers, and the set-up of a Software In-the-Loop (SIL) platform for the laboratory validation of new control, operation, and planning algorithms for smart grids management [25]. In SIL, an algorithm is usually tested with respect to the real network or system. For instance, a new control strategy for demand side management in distribution systems can be run in a separate machine and connected to the virtual model of distribution system running on a real time simulator.

As stated, the distribution grid needs to be first modelled for the specific application. The tool to implement the modelled grid depends on the real time simulation firmware configuration. We use Opal RT with eMEGAsim® configuration which requires MATLAB Simulink® as development environment. Therefore, the grid model is implemented in MATLAB Simulink using Matlab toolbox blocks, our developed blocks, and some external special blocks provided by Opal RT in an additional library. The interface between the development environment and simulator control is called RT LAB®.

2.3. Smart-grid simulation tool

As mentioned in Section 2.1, the *Integration Module* in Fig. 1 is in charge of correlating information coming from the Smart Grid with the output of the PV simulator for the same geographic area. In addition, this module provides features to enable the communication with the real-time grid simulator through the *Communication Software Adapter*, as shown in Fig. 2.

In its core, the *Communication Software Adapter* consists of two sub-modules: i) *UDP module* and ii) *REST adapter*. The UDP module interacts with the real-time simulation engine through a UDP server-client system: the UDP server receives and processes the information coming from the simulator, while the client pushes the input data into it. It is worth noting that we chose the UDP protocol because of its light-weight nature, which gives real-time application a good choice succeeding in real-time execution. The *REST adapter* parses the requests from the simulation engine and translates them into REST calls to remote web-services. Finally, the web-service response is retrieved by the *Communication Software Adapter* and its data are pushed into the real-time grid simulator again through the *UDP module*.

Fig. 3. Real time simulator receiving data links to the distributed PV models over the grid

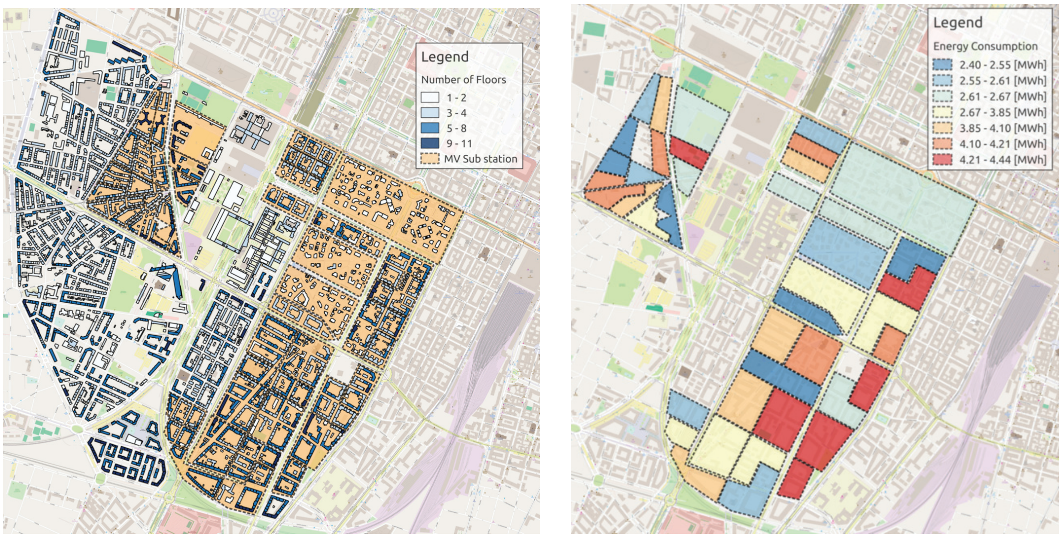
Considering the integrated simulation tool as a realized Software In-the-Loop (SIL), the environment which is the smart grid in our case, is executed on the real time simulator. Grid real time simulation module is responsible to emulate real grid behaviour facing different load or generation profile values, and provides the status of the electrical system in terms of power flows, voltage profile, etc. The signals coming from outside of the real time simulator are controlling or defining modelled prosumers behaviour by updating PV generation output. During the simulation the grid model requests the necessary values (active and reactive powers) to update modelled PV generation output, and receives the required data from the PV simulator through appropriate UDP blocks inside the real time model (Fig. 3). The grid model can be run for an electromagnetic transient simulation with 50 μs to 250 μs (or phasor simulation with a few milliseconds) time steps, while the new values of PV generation can be updated every 15 min.

The model is built with the SimPowerSystem (SPS) toolbox of MatLab Simulink. The ARTEMiS software from OPAL-RT is used to provide fixed-step solver dedicated to complex power systems. It is an add-in toolbox to SPS enabling hard real-time simulation of power systems. The main modelled components of the distribution grid are a three-phase voltage source in series with an RL branch as an equivalent model for the upstream high voltage (HV) grid connected to a slack bus, three-phase two-winding transformers, three-phase π section lines to model medium voltage (MV) lines and three-phase three-wire dynamic load models with external control of active and reactive powers to model the prosumers. The prosumers in our case study are (mainly) residential household as customers with their PV arrays on top of the building roofs as distributed producers. The net active and reactive powers of the prosumers are considered positive when the prosumer generation is lower than consumption.

3. Case Study

The proposed methodology has been tested using information about Turin, which is a city in the North-West of Italy. The case study area involves a district where the DSM, with a resolution of 0.5 m^2, and the MV grid topology are available. This area counts 2198 residential buildings connected to 43 MV/LV substations. Each substation serves an area whose extension depends on the number of connected households, as reported in Fig. 4(a). To evaluate the integration of PV systems in the district, a summer day has been simulated. During summer days, in Italy, the energy consumption of residential users is lower than in winter days [26] because residential households do not usually have air conditioning systems. On the other hand, during winter season, heating systems circulation pumps run almost all day long. In addition, sunny days in summer produce more electricity from PV systems and this can be a critical situation for distribution grids. Fig. 4(b) shows the daily energy consumption for each substation (consumption data were obtained through measurements in MV/LV substations). Energy consumption is not proportional to the area served by the sub-station, but rather to the number of households. Unfortunately, information about DNI and DHI are not available. Hence the *Solar radiation decomposition* module is used and the values of GHI radiation are retrieved, via web-services, from a weather station located in the center of the district. Finally, high quality mono-crystalline Si PV modules with efficiency $\eta_{pv} = 20.4\%$ in standard test conditions (STC) and thermal coefficient of maximum power $\gamma_{pv} = -0.38\%/°C$ have been considered.

The portion of the MV grid consists of a primary substation with three MV-22 kV busbars, each of which is fed by a transformer characterized by voltage ratio of 220/22 kV. For our case study, we selected 5 MV feeders derived from the HV/MV substation, which are feeding 49 MV/LV substations. 43 substations are supplying loads (mainly



(a) Substation areas with buildings (b) Substation daily energy consumption

Fig. 4. Case Study Area

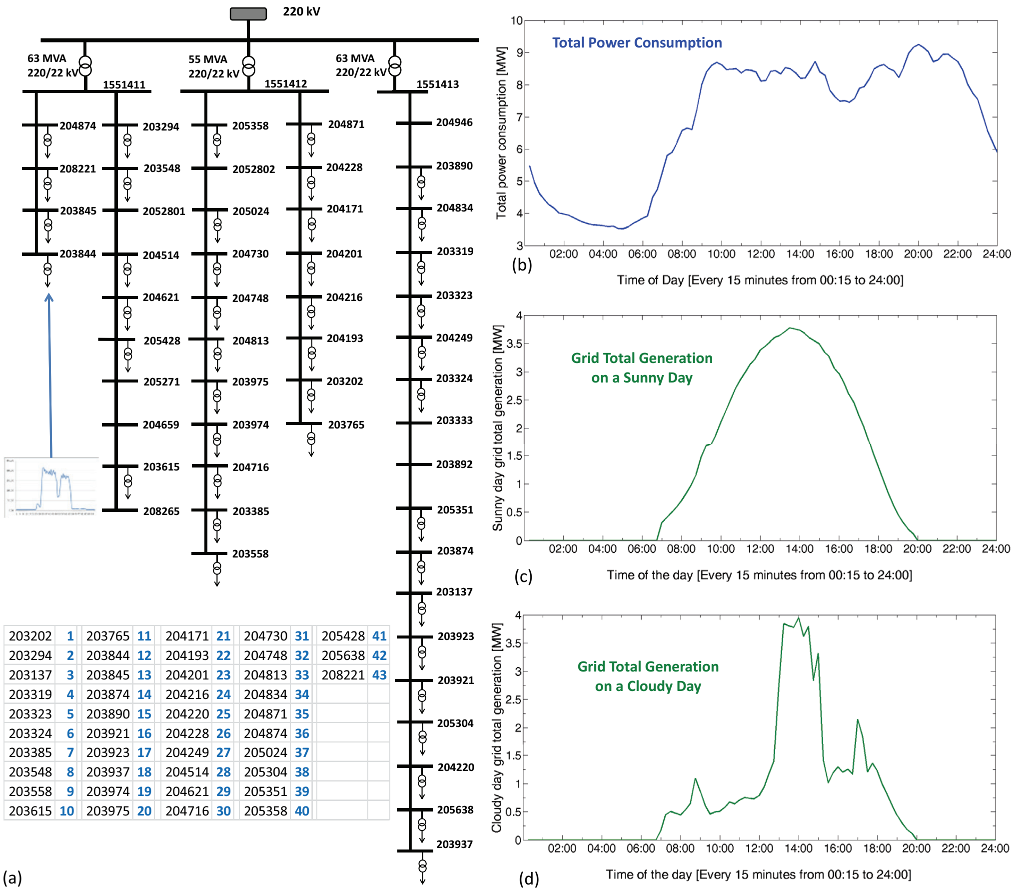
residential buildings). These substations are equipped with a MV/LV transformer characterized by voltage ratio of 22 kV/400 V and a nominal power of 400 kVA or 250 kVA. The total length of MV lines, mostly constituted by underground cables, is around 39 km (Fig. 5(a)).

The integrated tool proposed here, provides a basis to analyse the impacts of different levels of PV generation on the distribution grid operational performance. This tool will support decision makings for long term planning for integrating more PV generation as renewable energy sources in residential grids, especially when new regulations are being made to provide incentives to install PV arrays; infrastructure enhancement could be also taken into account in parallel. In other words, using this tool eases assessment of maximum PV penetration in residential grids based on existing network infrastructures.

In our case study, we test the usefulness and functionality of such an integrated real time simulation tool for the assessment of the system voltage profile. In distribution systems, tap changers of the HV/MV transformers at the primary substations would try to keep the voltage at the MV busbars at a certain level, by measuring and monitoring transformer current. When a transformer feeds several feeders, characterized by different PV penetrations, the voltage profiles at the secondary substations on the different feeders follow different profiles. This means that monitoring and regulating the voltage at the beginning of feeders is not necessarily sufficient for keeping voltages of all the substations of all the lines in the desired range. For example, in feeders where generation is higher, in some substations voltages may be above the admissible limit. In our case, the first feeder from the left is characterized by low demand, while its PV generated power is more or less the same as the others. In the second feeder, MV/LV transformers have greater sizes (400 kVA and 250 kVA), and consumption is higher than in the left one in which smaller transformers (160 kVA) are installed.

In this case study, we analyse a scenario in which almost all residential buildings install PV arrays on their rooftops, which reach their peak power on a sunny day of July. The PV generation module does not consider grid constraints and introduces PV generation with the highest possible penetration, considering the available surface areas on the rooftops.

The added-value of this integrated framework is the possibility of concurrently taking into account both real-like PV generation behaviour from one side, and grid behaviour and constraints on the other side.



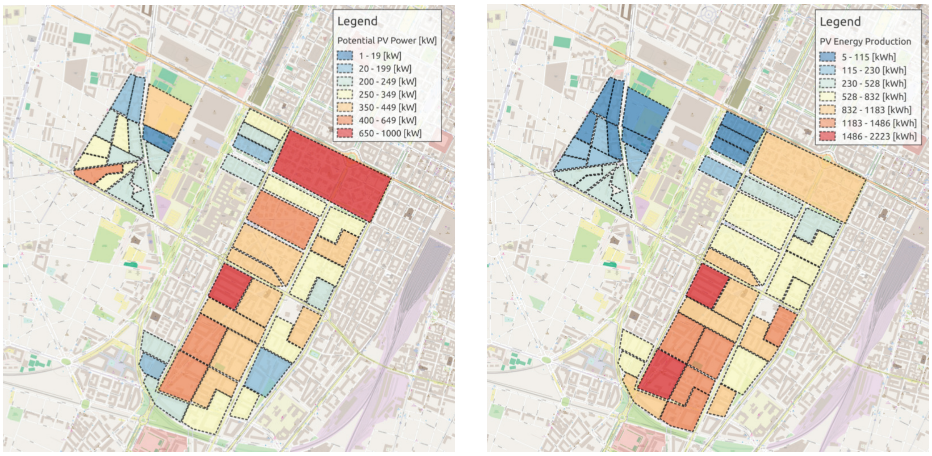
203202	1	203765	11	204171	21	204730	31	205428	41
203294	2	203844	12	204193	22	204748	32	205638	42
203137	3	203845	13	204201	23	204813	33	208221	43
203319	4	203874	14	204216	24	204834	34		
203323	5	203890	15	204220	25	204871	35		
203324	6	203921	16	204228	26	204874	36		
203385	7	203923	17	204249	27	205024	37		
203548	8	203937	18	204514	28	205304	38		
203558	9	203974	19	204621	29	205351	39		
203615	10	203975	20	204716	30	205358	40		

Fig. 5. Case Study electricity grid, total consumption and generation daily profiles

4. Results

In the district under analysis (see Section 3), among all the building rooftops the *Suitable Area* module identified 944 areas, equivalent to 71595.53 m^2, suitable for deploying PV systems with a nominal power potential equal to 14.21 MW. The distribution of power and energy production for each MV substation area during a sunny day in summer is shown in Fig. 6(a) and Fig. 6(b) respectively. As the simulation process considers also the shadows of surrounding buildings and vegetations, rooftops areas with high power production potential can have an energy production impact lower than areas with low power production potential (see Fig. 6(a) and Fig. 6(b)). This is also highlighted by Fig. 5(c) and (d) that show the power generation profile for the whole district during a sunny and a cloudy day respectively. During the sunny day, the peak power production is around 3.77 MW and the energy production is equal to 28.41 MWh. On the other hand, during the cloudy day, it is around 3.94 MW with an energy production of 16.95 MWh. The peak power production does not reach the nominal peak power in either of the two cases. The higher peak power reached in the cloudy day can be explained through the phenomenon of irradiance spikes caused by broken clouds (ISBC) [27] or by a lower temperature of the PV arrays.

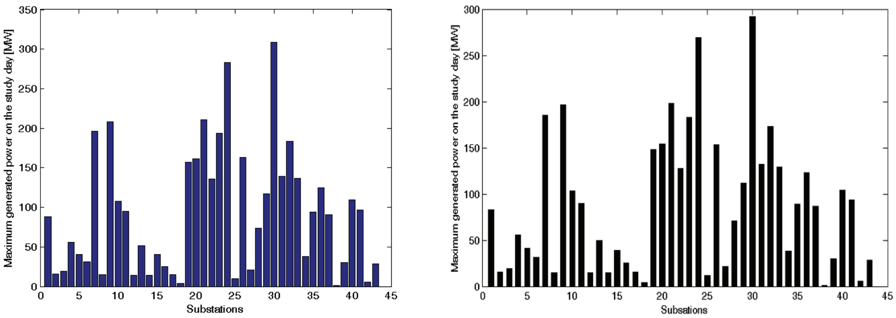
Having set up the integrated simulation platform, one can assess different impacts of PV power penetration on the distribution grid by applying different levels of PV integration. For instance, substations voltage profiles can be assessed considering PV generation distributed uniformly and homogenously over the area, or on the contrary, PV



(a) Sub station areas with buildings

(b) Total PV generation profile sunny day

Fig. 6. PV potential and energy production



(a) Sunny day

(b) Cloudy day

Fig. 7. Maximum PV generation of each MV/LV substation

installation only on some lines. As stated in section 3, increasing PV penetration in only some feeders supplied by the same HV/MV transformer and leaving others with only consumption may cause voltages above the admissible limit on the substations with high PV penetration. The other effect can be observed on cloudy days when generation profiles change dramatically within a few seconds. If a huge generation drop occurs exactly in the ascending period of consumption profile, in high PV penetration scenarios, a large power deficit will be experienced. This can cause low voltage especially on terminal substations, or even a slight frequency deviation in the upstream transmission system in case a large interconnected area of distribution systems concurrently faces the same situation.

To demonstrate an application of the proposed integrated simulation platform in PV penetration assessment, in this section we present some results of simulating the distribution grid behaviour in case of a high PV penetration. For this case, a sunny day scenario is used when all installed PV arrays are in operation. The MV/LV transformers at the secondary substations are modelled based on the existing transformers in the real network, which were installed without considering the new PV generation capacity. Maximum aggregated generated power of each substation on the study day is shown in Fig. 7(a).

Transformer capacity is based on maximum apparent power in [kVA] and can be considered for both power absorption and injection (the red continuous lines in Fig. 8). All values of power generation and consumption are calculated for every 15 min of the study day, therefore there would be 96 snapshots of the systems status. To reach the worst

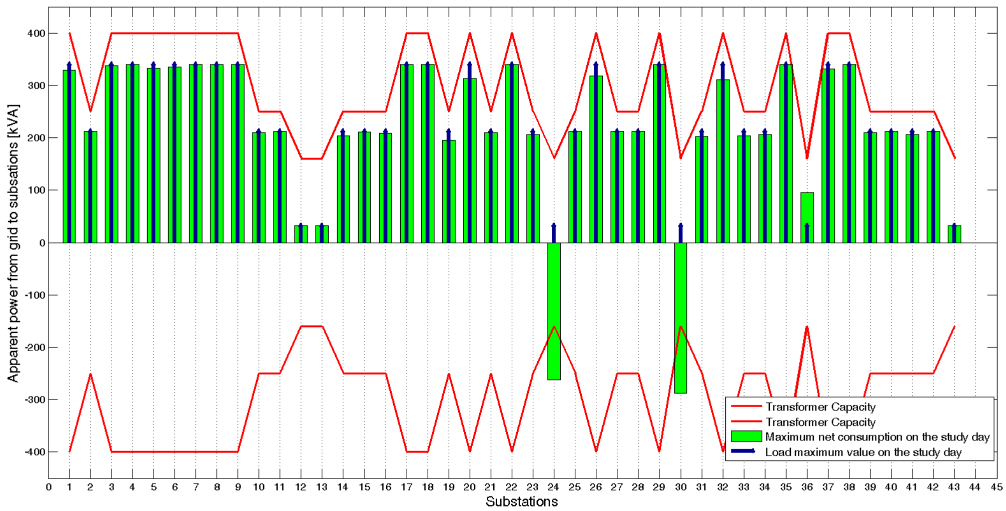


Fig. 8. Network results

scenario, we consider the maximum net consumption (subtracting local generation from local consumption) of each substation during the study day, indicated with large green bars in Fig. 8. As shown with narrow dark bars, the maximum load consumption of all substations is within the transformer capacity range, while integrating PV generation would cause violations in 2 substations (24 and 30 in Fig. 8). The maximum net consumption in these 2 substations exceeds the transformers capacity due to high amount of PV generation and low consumption. This highlights the fact that in cases where local generation is much more than local demand, either the installation of PV arrays should be reduced or grid infrastructures in terms of transformers (and also cables/lines) should be enhanced to tolerate reverse power injection from substations to the grid.

5. Conclusion

In this paper the authors presented an integrated real-time platform for the assessment of the impacts of PV distributed generation in smart grids. The platform is constituted by two main components, a PV simulator and a real-time distribution network simulator. The two components are interconnected over the Internet through a communication software adapter. The proposed tool allows for the simulation of the power produced by PV generators on buildings rooftops under real sky conditions, and for the analysis of the distribution grid behaviour in this distributed generation scenario. The tests carried out on a case study based on a district of Turin, Italy, show that the distribution network, in the actual configuration, may not be ready to accommodate all the generation capacity that can be installed if all the available rooftop surface is exploited. The presented platform can be useful, in the future, to analyse different penetration scenarios, to test new operational procedures for the distribution network, to verify the impact of new connection rules and new regulations.

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