Applied Energy 125 (2014) 103–113

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Improving photovoltaics grid integration through short time forecasting and self-consumption

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HIGHLIGHTS

- Uncertainty in PV generation forecast is a drawback for grid integration.
- Self-consumption of distributed PV reduces the effect of forecast uncertainty.
- Active Demand Side Management and local storage increases self-consumption.
- Experimental results and simulations are presented.
- Error on electricity exchanged with the grid is reduced to 2%.

ARTICLE INFO

Article history:
Received 18 January 2013
Received in revised form 17 July 2013
Accepted 23 March 2014
Available online 16 April 2014

Keywords:
Distributed PV
Energy forecast
Demand Side Management
Grid integration

ABSTRACT

The uncertainty associated to the forecast of photovoltaic generation is a major drawback for the widespread introduction of this technology into electricity grids. This uncertainty is a challenge in the design and operation of electrical systems that include photovoltaic generation. Demand-Side Management (DSM) techniques are widely used to modify energy consumption. If local photovoltaic generation is available, DSM techniques can use generation forecast to schedule the local consumption. On the other hand, local storage systems can be used to separate electricity availability from instantaneous generation; therefore, the effects of forecast error in the electrical system are reduced. The effects of uncertainty associated to the forecast of photovoltaic generation in a residential electrical system equipped with DSM techniques and a local storage system are analyzed in this paper. The study has been performed in a solar house that is able to displace a residential user's load pattern, manage local storage and estimate forecasts of electricity generation. A series of real experiments and simulations have carried out on the house. The results of this experiments show that the use of Demand Side Management (DSM) and local storage reduces to 2% the uncertainty on the energy exchanged with the grid. In the case that the photovoltaic system would operate as a pure electricity generator feeding all generated electricity into grid, the uncertainty would raise to around 40%.

1. Introduction

Over the last years the amount of photovoltaic power installed worldwide has been increasing steadily [1]. This growth responds to various reasons, among which stand out the increasing awareness of global warmth caused by greenhouse emissions, the inevitable exhaustion of traditional energy sources in the following decades (fossil fuels) and the need for countries to assure energy self-dependence [2,3]. Photovoltaics (PV), as well as other renewable energies, provide safe and clean electricity and, moreover, can play an important role in the solution of the aforementioned problems. The growth ratio of the PV installed capacity increases every year, so that the cumulative capacity shows an exponential behaviour [1]. It is noteworthy that this trend has been maintained also in recent years when some countries, particularly in Europe, started to cut down on subsidies and feed-in-tariffs. As a consequence of this growth the effect of photovoltaic power connected to public utilities begins to be noticeable for the overall system. For example, in Spain and Germany the share of electricity

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http://dx.doi.org/10.1016/j.apenergy.2014.03.045
0306-2619/

produced by grid-connected PV during 2010 was 2.3% and 1.9% respectively [4,5]. The share of electricity produced by PV and other renewable energies is expected to grow in the following years [6–9].

As the share of electricity produced by PV increases, the need for photovoltaics to be fully integrated into electricity grids arises. Fully integration of a generator into the grid requires that the electricity produced by the generator is known beforehand. With this knowledge, the generator can be included in grid planning and it would be possible to dynamically adjust its output in response of real time demands from the grid. Traditionally, photovoltaic energy, together with other renewable energies like wind, has been considered to be a non-controllable, unpredictable electricity source. In consequence, it has not been regarded as a reliable energy source by grid operators. The unreliability of PV is due to its dependence on meteorological conditions: irradiance and temperature. If these two meteorological variables could be forecasted with sufficient precision, it would be possible to estimate the electricity production of a PV system. In addition, photovoltaics will become a more reliable electricity source.

The use of forecast techniques to enable grid integration of PV electricity [10,11] (and also other renewable energies such as wind [12,13]) has been previously addressed in the literature. Despite efforts to improve forecast techniques, they still incur in high error rates. For this reason, some authors have suggested alternative schemes that would make possible the goal of grid integration. Some of these schemes are the use of local storage in combination with renewable energy generators in order to rectify deviations between forecasted and produced electricity [14] or the combination of a large amount of PV generators distant from each other so individual errors are independent and the overall forecast error is reduced [6].

At the same time that renewable energies are being deployed and are expected to play a major role in the generation of electricity, the traditional conception of distribution grids as passive drains of electricity is shifting towards a more active one with the inclusion of Demand-Side Management (DSM) and storage which allow demand to adapt dynamically to generation [15–19]. This new paradigm of distribution grids is based upon the smart grid concept [20,21]. This paper proposes a novel mechanism for integrating small sized PV generators in the residential sector that brings together the aforementioned elements: PV forecasts, DSM and local storage. Active Demand-Side Management (ADSM) is a new concept derived from the addition of automatic load control to DSM strategies [22]. In this situation, the concept of self-consumption arises, i.e. the local consumption by loads of the electricity generated by the PV system. Self-consumption also provides an alternative for photovoltaics exploitation on the current scenario of increasing electricity retail prices and decreasing feed-in-tariffs. Users can reduce the electricity bill by the use of their own generated electricity. In some countries, like Italy, in addition to the financial incentive gained by selling electricity to the retailers there is also an incentive for the self-consumption of PV generated electricity [23]. From a technical perspective, some authors have pointed that distributed PV generation can provide directly as much as 20-25% of a city demand if no additional measures are taken and 50-75% of electricity demand if Demand-Side Management and storage are used [24–26].

Although this approach to PV integration in the grids has several advantages (e.g.: mitigation of forecast error through battery usage, displacement of peak demand and flattening of demand profile, reduction of system losses associated to transport and distribution, provision of ancillary services like voltage control via reactive electricity feeding), there is no previous results on this subject apart from theoretical studies. This paper explores, as proof of concept, this possibility for PV integration in the residential sector to demonstrate that it is feasible and that the uncertainty in PV generation can be made negligible.

The remainder of this paper is as follows. Section 2 presents Magic Box, a solar house, which combines the aforementioned elements: PV generation, local electricity storage and a control system which is responsible of performing the ADSM, managing the storage and forecasting electricity generation. Section 3 introduces the methodology employed in this study to evaluate the achieved level of self-consumption. Section 4 presents the results of a measurement campaign carried out on Magic Box. On Section 5 a comparison of two of the most popular forecasting techniques, numeric weather prediction models and time series analysis, is presented. Conclusions are summarized on Section 6. Finally, two annexes which describe the forecast models employed are appended to the paper.

2. Magic Box and GEDELOS-PV system

Fig. 1 shows a block diagram of the system composed by the combination of Magic Box and the GEDELOS-PV system. Black solid lines indicate the power/energy flows between the different elements capable of delivering electricity -PV generator, storage and the grid- or consume it -loads, storage and the grid-. The blue dotted arrows show the information received by the ADSM system from the different system elements. Finally, the red dashed arrow shows the flow direction of the actuation commands from the ADSM system to the loads. The user interacts with the system through the loads set-up via the ADSM system. Magic Box and the GEDELOS-PV system are explained in detail below.

2.1. Magic Box

Magic Box is an energy self-sufficient solar house located in the grounds of the Technical University of Madrid, Spain (UPM). Magic Box was the first house from a European university to take part in the international competition Solar Decathlon [27,28], it is used now as a research laboratory at the UPM. This solar house has been used to assess the effect of the combination of PV generation forecasts, load management and local storage on the electric grids. The house is based on AC topology, where electricity is exchanged between the different elements -PV generators, storage, loads and grid- through an AC bus. This topology does not impose an explicit hierarchy to the energy elements and, therefore, it increases system scalability.

2.1.1. Photovoltaic system

The PV system produces energy that can be: either used locally by the loads, stored in the batteries or fed into the grid. It is divided into five independent generators of monocrystalline silicon technology distributed in four different south-oriented surfaces whose tilt angles are: 12.5°, 25°, 40° and 90°. Each PV generator is connected to a single string-type inverter. The combined peak power of the five generators is 6.2 kW_P.

The photovoltaic system also incorporates a meteorological station and monitoring equipment. The meteorological station has the following sensors: four reference PV sensors for the measurement of irradiance [29] (one cell for each tilt angle) and a PT-100 resistor for the measurement of ambient temperature. The monitoring equipment records every five minutes values from the sensors in the meteorological station as well as AC and DC power, current and voltage from the five PV generators. Additionally, a precision energy meter (class 1 [30]) records the AC energy produced by the whole PV system every minute.