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Impact of Residential Photovoltaic Generation in Smart Grid Operation: Real Example

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Abstract

This paper assesses the impact of residential photo-voltaic (PV) generation on the operation of a distribution smart grid in Chile. In particular, we focus on distribution losses and bus voltage regulation. This smart grid is composed of three hundred residential customers and belongs to the Central Inter-connected System (CIS) of Chile. A set of scenarios with different daily load profiles and generating levels are considered. The demand of each client is obtained by measuring the total demand at the distribution transformer and is disaggregating it using consumption profiles. The possibility of reactive power injection through the PV power converters is also considered. To estimate its maximum impact, the reactive power injection is calculated by minimizing network losses through optimal power flow. The location of the PV generation is a random variable with uniform distribution, and the expected losses and voltage profiles are determined using the Monte Carlo method. Three levels of PV generation are considered, 5%, 10% and 15% of the total distribution load. As was expected, the voltage in all the buses of the system increases when reactive power is injected by the power converters of the PV generation. In addition, losses compared to the case without PV generation, decrease by 44% in the most favorable scenario and 1% in the worst case. An estimation for the 40% of residential customers in Chile, considering only 5% penetration of PV generation, give as more than 170.000 MWh of savings in generation per year.

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Keywords: Photovoltaic generation; distribution system; Desegregation of the demand; Monte Carlo method.

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1. Introduction

In recent years, energy demand in Chile has increased at an annual rate of approximately 5%, and will remain with this tendency according to [1]. Moreover, the continuous increment in the price of fossil fuels, depletion of exploitable water resources and high social impact to which these projects are subjected, have created the conditions for non-conventional renewable energy (NCRE) to enter into the electricity market.

NCRE projects such as solar and wind, have the advantage of having a low environmental impact, they are better received by the community and have lower design and installation time delays. Among the different types NCRE, the PV generation is of special interest because its manufacturing cost has decreased from US$76/Wp

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in 1977 to US$0.74/Wp in 2013 [2]. In practice, PV generation can be used in high power installations (order of MW), as well as residential implementations. Due to high levels of radiation in Chile, PV is a particularly attractive generation technology.

In Chile, the Law 20.571 establishes that end users with generating capability are entitled to inject their energy excess to the grid, as long as the energy is provided by NCRE or efficient co-generation and have an installed capacity equal or less than 100 kW [3]. At the same time, the utility is obliged to buy the injected energy; where the selling price is given by the Regulation Decree N^{o}71 [4]. Furthermore, other technical aspects of the installation and operation of these type of generation technologies are defined in the Technical Standard for Connection and Operation of Low Voltage Generation Equipment [5].

Considering the enactment of the above mentioned technical standard (Law 20.571), together with the reduction on the PV generation costs, a boom in PV installations is expected. However, there is no certainty of the effects that PV generation would have in the grid. Most authors evaluate the penetration of distributed generation (DG) in smart grids with a deterministic approach [6] and [7], i.e. a scenario is chosen according to technical criteria. On the other hand, it is a common practice to consider the power injection of the DG through several fixed points, where only the quantity and not the location is changed when penetration varies. Examples of this procedure can be found in [8] and [9].

In this article, the impact of PV generation in distribution losses and bus voltage of a smart grid is evaluated. The injection point is considered as a stochastic variable .For a 10% penetration, 28 random injection points over a universe of 284 are required, so, Monte Carlo Method is used to restrict the number of experiments to 4000. For each experiment, a load flow was executed to calculate the bus voltages and distribution losses. The reactive power effect is evaluated by running an optimal power flow per experiment.

The paper is organized as follows. In Section 2 a description of the the system is presented, which includes the disaggregation problem, smart grid modeling and stochastic technique. An application on a real smart grid is developed in Section 3, where a description of the grid considering PV penetration and the applied power flow techniques are included. The studied scenarios are presented in Section 4 considering the PV generation and the influence of the power converters. On Section 5 the main results of the study are shown, where power, energy and voltage are depicted in time evolution graphs. Finally this article ends with some concluding remarks and future research in Section 6.

2. Methodology of the Study

2.1. Description of the problem

This work is focused on the effect of residential PV generation randomly located in a low voltage network. This requires a significant amount of network data; parameters of the lines, customer consumption pattern and time of each customer. These data is not available in Chile, so it is necessary to make an estimation of the energy consumption.

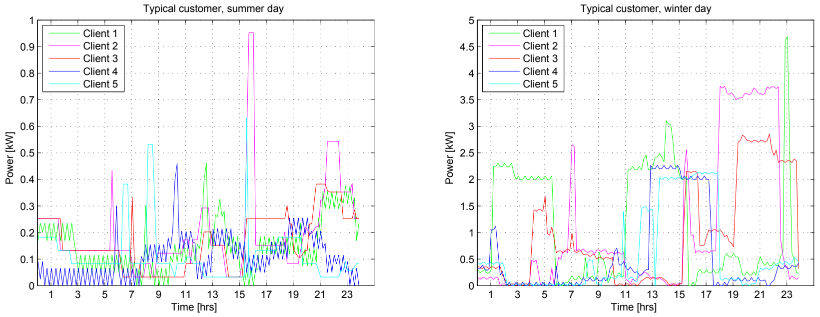
To overcome the lack of information we have defined cases of interest such as days of the year for which the conditions of integrating PV generation could be critical. Following the same criteria, and recalling that the power inverter is an active-front-end, the injection of reactive power to the grid is considered.

2.2. Disaggregation of the demand

In order to perform the simulations we required to meet the demand of each customer, yet we only count with the demand on the distribution transformer per hour in a standard day of winter and during summer. Some studies tackled the problem of the demand disaggregation by assigning randomly a demand to each customer until the addition matches the consumption upstream. This approach requires extensive database of consumer behavior which is obtained through customers surveys [10].

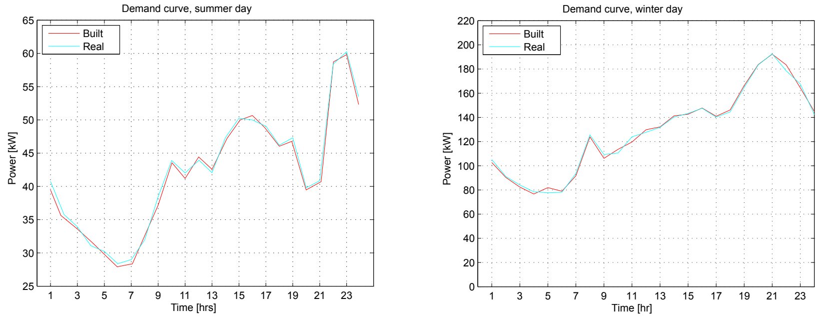
Another possible solution to this problem is disaggregate the total demand on the transformer in relation to the nominal power of each consumer; yet this method does not consider the energy consumption diversity among customers [11].

Despite we can not relay on a database to apply the method of disaggregation [10], 26 different profiles for winter and 26 other for summer are created by means of the nominal power of customers and the monthly energy consumed. In figures 1(a) and 1(b) summer and winter consumption profiles of five different clients, are depicted.



(a) Summer day (b) Winter day

Fig. 1. Examples of consumers



(a) Summer day (b) Winter day

Fig. 2. Real and assumed demand

To create more variability among consumers, each profile is generated with different household appliances used at different times of day. Once the profiles are defined they are multiplied to reaches the number of grid clients, then are added and shifted in time in order to match the measured power in the transformer. The shape measured in the transformer and the one created through this method are presented in figures 2(a) and 2(b).

2.3. *Grid modeling and operating conditions*

The network loads are considered as constant power, which implies that the product of voltage and current must be kept in a single value for each operating point of the system [12].

The study was performed at intervals of one hour and considering steady state operation.

2.4. *Stochastic processing: Monte Carlo method*

Since the location of generation is a random variable, an additional tool is required to evaluate it. Given that, Monte Carlo method is a probabilistic method that can deals with variables (n) of multiple possible values ($x_1, x_2, ..., x_n$), where each one has a probability $p(x_i)$. This technique is useful tool to solve complex mathematical functions that can not be evaluated analytically, therefore, is an appropriate technique to address this problem. The results analysis is performed by calculating the expected value, as shown in expression (1), which represents the *average value* that is expected to occur.

$$E[X] = \sum_{i=1}^{n} x_i p(x_i) \tag{1}$$

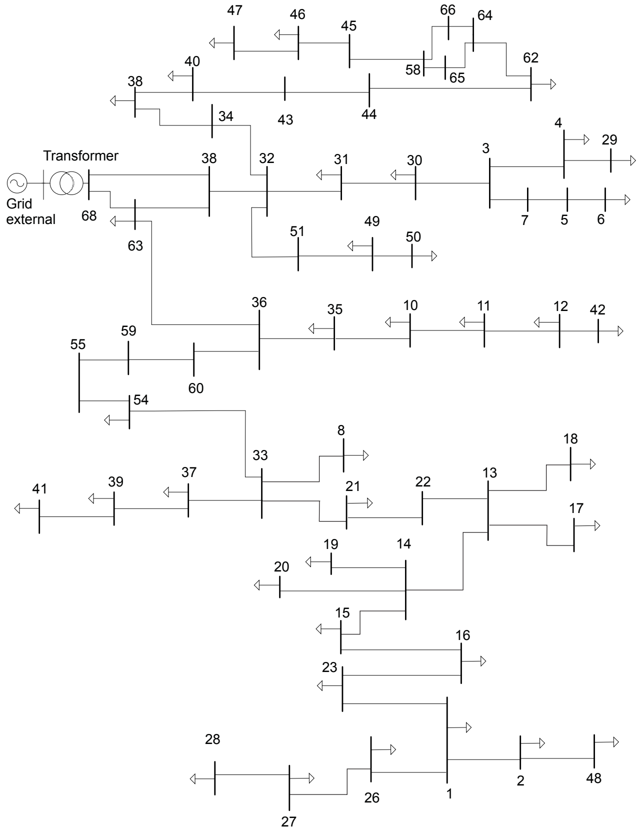


Fig. 3. Low voltage system used in simulation

There are cases where the total number of values that the random variable can take is so large that in practice its not possible to evaluate them all. Even though, there exist techniques [13] to deal with this problem by reducing the number of scenarios. An other strategy to achieve a proper result it is based on accurately choose the amount of scenarios, therefore the expected value of the losses is calculated together with its corresponding standard deviation (S, see relation (2)).

$$S[X] = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - E[X])^2} \tag{2}$$

The appropriate number of scenarios is estimated by calculation of the expected value and standard deviation with reduce data, which is gradually increased until the expected value and standard deviation is stabilized [14]. The selection of the next data for the calculation is done randomly.

3. Application

3.1. Power smart grid description

The low voltage grid (380V) on which the simulations are performed is composed of 284 residential clients, 69 buses and 70 lines. This smart grid is part of a concession area of a distribution company in Chile, the general scheme is shown in figure 3.

Table 1. PV genertaion clients acording to penetration

Penetration	Clients
5%	14
10%	28
15%	35

3.2. PV penetration

In this study, 5, 10 and 15% PV penetration is considered. In order to achieve accurate results, these percentages are calculated with respect to the number of clients and not in terms of the installed power. Thus, if the penetration increased it means that there is an increment in the number of clients with PV panels.

Table 1 shows the number of clients for the different penetration values.

3.3. Power flow

By using MATPOWER [15] (from Matlab) the equations of the power flow shown in (3) and (4) were solved.

$$P_i = \sum_{n=1}^{N} |\mathbf{Y_{in}}||\mathbf{V_i}||\mathbf{V_n}| cos(\theta_{in} + \delta_n - \delta_i) \tag{3}$$

$$Q_i = -\sum_{n=1}^{N} |\mathbf{Y_{in}}||\mathbf{V_i}||\mathbf{V_n}| sin(\theta_{in} + \delta_n - \delta_i) \tag{4}$$

3.4. Optimal Power Flow

The optimal power flow technique is used in this study to minimize losses. This minimization is performed by injecting reactive power with the power converter (inverter). The limit of reactive power that can be delivered is given by the active power generated at time i (which is given by environmental conditions, mainly radiation) and the apparent nominal power of the inverter according to the relation (5).

$$Q_{max} = \pm \sqrt{S^2 - P_i^2} \tag{5}$$

On the other hand, the function shown in relation (6) minimizes operation costs according to cost functions for active ($f_i^P(P_g^i)$) and reactive ($f_i^Q(Q_g^i)$) power.

$$min \sum_{i=1}^{n_g} f_i^P(P_g^i) + f_i^Q(Q_g^i) \tag{6}$$

To minimize losses and not the costs, the function (6) is modified; first the cost of reactive power is removed, then a linear active power cost function equal to all generators is assigned. The developed technique is shown below.

$$min \sum_{i=1}^{n_g} f_i^P(P_g^i)$$

$$min \sum_{i=1}^{n_g} f^P(P_g^i) = f^P(P_g^1) + f^P(P_g^2) + ... + f^P(P_g^{n_g})$$

$$f^P = AP_g^i + b$$

$$Donde \quad A, b \epsilon \Re$$

$$\sum_{i=1}^{n_g} P_g^i = P_G \tag{7}$$

$$min \sum_{i=1}^{n_g} f^P(P_g^i) = min \quad AP_G + n_g b \tag{8}$$

$$Finalmente,$$

$$min \quad A(P_D + P_{loss}) + n_g b \tag{9}$$

The flow diagram of the programming technique is depicted in figure 4.

4. Cases of study

The PV system consists of one or more PV panels whose output is connected to an inverter, which converts the direct current into alternating current. One of the cases to compare to the base case is the injection of active power to the grid (*P*).

This power converter (inverter) also has the capability to inject reactive power, for which requires the installation of a capacitor in the DC bus. Therefore, whenever is needed we can use all the thermal capacity of the inverter to inject reactive power to the system. For this reason the simultaneous injection of active and reactive power (*P* and *Q*) will also be studied.

4.1. PV generation

The power of each PV system is $P_n = 1,36kWp$, while the inverter has a nominal power $S_n = 1,5kVA$. According to figure 5, during winter, great disparity can be seen in PV generation. Therefore, as it is depicted in figure 4.1, two generation profiles are used.

On the other hand, during summer a very different behavior is presented, the generation is practically the same for each day of the period, as shown in figure 7. For the above mention, only one profile per day will be considered (see profile in figure 8).

5. Results analisis

The results given by the power flows demonstrate that a reduction of losses is achieved compared to base case, this results are depicted in figures 9(a), 9(b), 9(c) and 9(d). In this figure are included the base case (SG), injection of active power (*P*), injection of active and reactive power (*P* and *Q*) and the last case where the reactive power injection is performed when ever is needed (PyQs). As was expected, the losses reduction is proportional to the penetration.

The figure 10(a) shows the average voltage of all grid buses for one day. As can be seen in the figure, not only the reactive power injection has a main impact on the voltage regulation (increase), but also the injection of active power has a great contribution in this respect.

Even thought there is a limit to the reactive power injection (mentioned in section 3.4), it is not exceeded at any operation condition or penetration level.

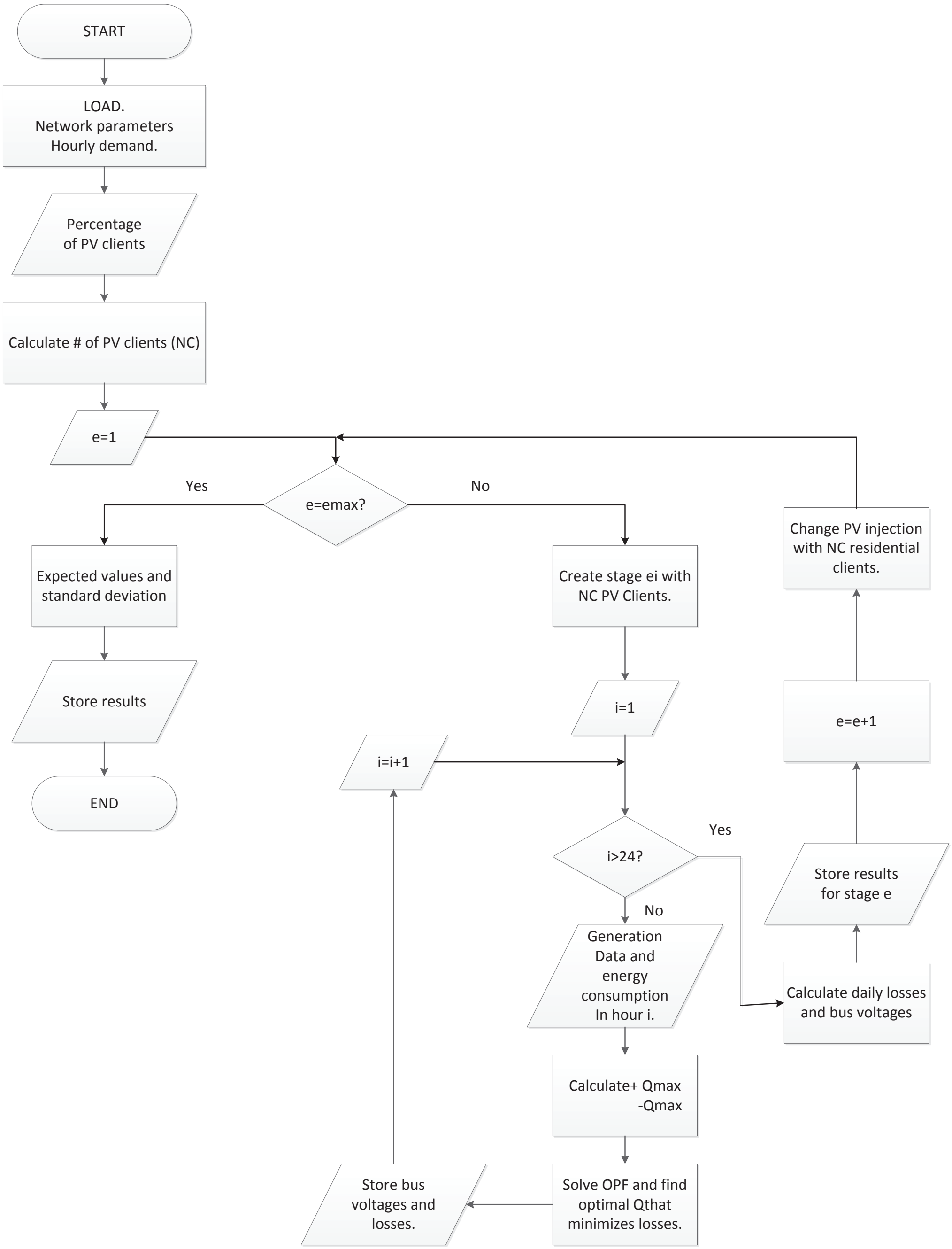


Fig. 4. Simulation flow diagram

6. Conclusions

The method used for demand disaggregation – creating different profiles of residential consumption which are assigned to the total number of clients and shifting them one respect to the other – led us to a result that, in

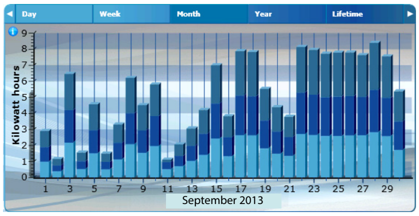


Fig. 5. Generated power during September

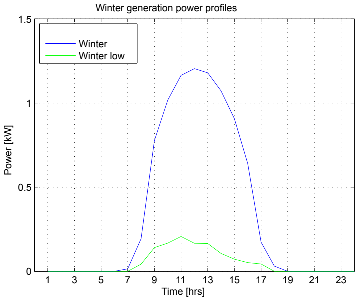


Fig. 6. Daily profile of the power generated in winter

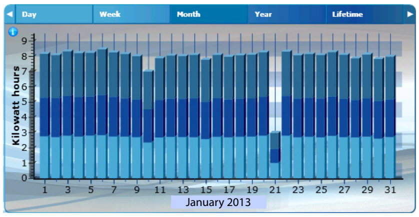


Fig. 7. Generated power during January

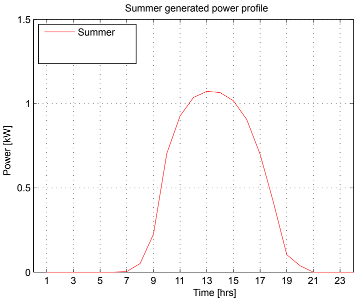
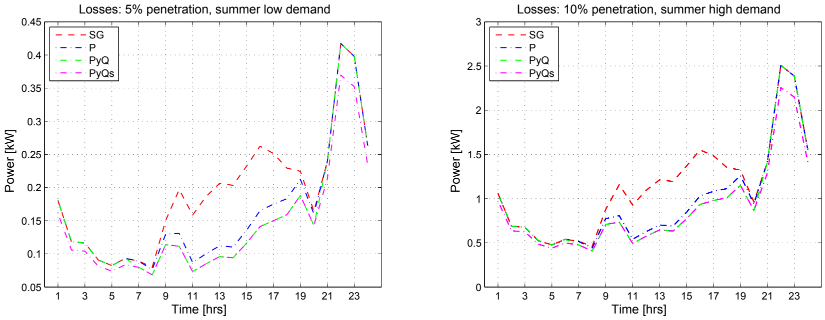


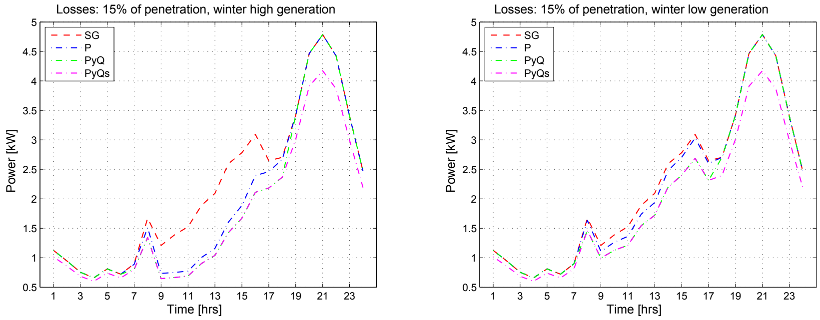
Fig. 8. Daily profile of the PV power generated in summer

comparison of what is stated in literature (using apportionment), is more realistic. Moreover, the outcome of the demand disaggregation over the active power assuming a constant power factor $PF = 0.93$, has better variability among customers (close to real behavior).

The performed analyzes indicates that the PV generation is a powerful tool to control bus voltage regulation.

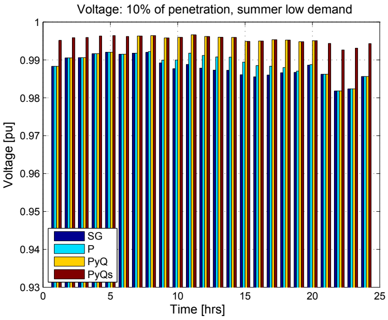


(a) Summer low demand (b) Summer high demand



(c) Winter high generation (d) Winter low generation

Fig. 9. Losses comparison for different levels of penetration



(a) Bus avarge voltage

Fig. 10. Low demand during summer, 10% of penetration level

As was expected, in operation with low radiation, i.e. mainly winter, the capability of active power generation is limited and so it is the control of bus voltage regulation.

The injecting of reactive power turns to be a practical and low cost solution to reduce losses and to improve voltage bus regulation for all levels of penetrations and scenarios. Although the reduction in losses is a direct consequence of the voltage increment, for clients connected in the extreme part of the smart grid can be affected for the lack of voltage regulation. Moreover, the increment of bus voltage and losses reduction is proportional to the number of generation connected buses.

Despite the low utilization factor of the PV generation (20% in this work) its active power generation is meaningful in terms of operation control of electrical variables. Furthermore, and considering that the reactive power market is being subject of study in the late years [16], the installation a PV generation incorporating reactive compensation is more attractive in terms of profits and costs. Considering the above mention, the operation of the PV generation as smart grid (bus voltage regulation and losses reduction) should serve as an incentive for extending the implementation of this technology.

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