Photovoltaic Inverter Scheduler with the Support of Storage Unit to Minimize Electricity Bill

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Abstract. The increase of distributed generation in several countries has led to new legislation that allows the owners to use the energy obtained from them in three possible ways: use the energy to face own consumption such as on-site generation, sell energy to the grid as a producer, or finally, do both according to context of operation. In this way, these technologies can be more easily introduced to the average public if there is a managing application that can represent the interests of its owners and perform the appropriate measures. This paper proposes a methodology for the management of different available technologies owned by a prosumer, analyzing the possible role it can have and what type of scheduling can be made, operating in the third way mentioned before.

Keywords: Energy management · Photovoltaic · Scheduling · Self-consumption

1 Introduction

In recent years, there has been an exponential increase of renewable generation amongst several countries, mostly due to the necessity of reducing their energy dependency on fossil fuels or pollution [1]. A known example is the European Union that imposed deadlines regarding energy to a more sustainable future [2, 3].

The increase of the number of consumers with generation units achieved a new concept: the prosumer [4]. An entity capable of both consuming and producing at the same time, i.e. a power node within itself [5]. Although the legislation that defines the activities of such an entity didn't accompany their implementation at first, it is now reaching a high development state where the prosumer is a very important part of power systems, and future of smart grids [6]. Moreover, when integrating Demand Response (DR), the modification of load profile in response to monetary or price signals thus providing flexibility [7], the consumer goes from a passive entity in the energy system, to one of the most active by managing both local consumption and generation resources. In this way, the consumer is of the upmost importance to the future of power systems, especially for the full implementation of smart grids.

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Distributed generation (DG) is mainly implemented by prosumers, with the installation of small-size generation units that, near consumption, has several advantages for the power system. Per example, DG can have a relevant role in voltage control and system losses [8]. The development of renewable technologies has caused an increase for their implementation as DG, namely, photovoltaic (PV) and wind. These two types of generation have several aspects that make them the most used, per example, PVs' easy installation, endurance, and variety of application, are the features that make this technology have a huge potential regarding its implementation in several sectors, as residential buildings [9]. Wind is difficult to install near populated areas due to their level of noise and turbulence. In the smart grid context, prosumers offer an adequate solution for the implementation of DG at the same time that can supply flexibility to the power system through demand-side management [10].

The concept of demand-side management implicates several topics, of which DR belongs to, together with energy efficiency, spinning reserve, and time of use [11]. DR is defined as the modification of the typical load profile, is response to monetary or price signals [12]. Monetary signals are incentive-based DR, since the consumer is induced to participate in an event following the interests of a third party. As for price-signals, these are price-based DR where the consumer chooses or not to respond, however, these will have influence in the consumer's electricity costs, since high rates are applied to induce load reduction. The management of demand-side allows the operators and prosumers to adjust load according to generation and insure cost reduction for demand at costly times [13, 14]. When considering that multiple entities need to communicate between each other, and interact at a decision/control level (such as, the implementation of DR programs and load modification), a relevant concept arises to define this mechanism, multi-agent systems. These are defined as distributed and autonomous entities that can be intelligent or not, but moreover, can allow for interaction between several systems. In a smart grid context, energy management systems can be individual agents that act and decide, upon previously defined rules or in an intelligent way, the path to improve operation. Moreover, if participating in DR programs defined by another agent (e.g. grid operator), management systems can automatically apply these considering some restraints.

The present paper addresses this topic by providing a methodology for an agent, that in this case is the consumer. The consumer is provided with an independent management that approaches the several resources capabilities and contributions for the minimization of energy bought from grid. With this methodology, the consumer can interact with upper-level entities (e.g. grid operator), to better manage its operation.

2 Proposed Methodology

The proposed methodology enables the optimal scheduling of the consumer's resources to minimize the costs of operation, therefore, to lower the electricity bill. The resources considered are the Main Network (MN) to which the consumer is connected, PV systems, energy storage battery, and consumption flexibility through load shedding. The consumer is involved in a time-of-use tariff program and it is assumed that energy injection in grid is possible and remunerated. The methodology is modelled to be implemented in different consumer conditions and number of resources. The following Fig. 1 shows the context behind the development of the proposed methodology, considering a household consumer, however, it can be applied to other types of consumers that are also producers (prosumer). The methodology considers that PV generation is free to use by the consumer, since it is underlined that the system belongs to the consumer. In the opposite, costs for the use of PV must be added to the objective function and energy supply priorities must be reviewed.

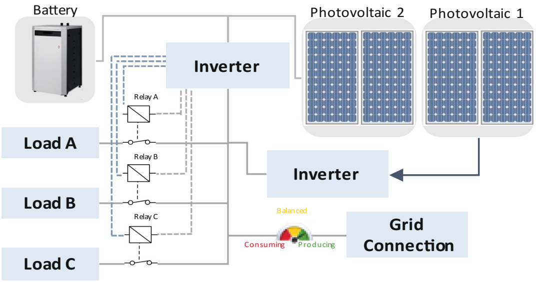

Fig. 1. Implementation context for the proposed methodology.

In the present paper, it is considered that PV has priority above all others, meaning that the PV generation, if available, will always be consumed, either by the load's necessities, battery charge, or injected in the MN. The grid's interaction is assumed as bidirectional, however there may be cases where thus is not allowed due to limitations in the physical network or in the legislation currently applied. In these situations, usually the on-site generation is mainly used for own load without injection in the MN. Also in Fig. 1, it is shown that up to three loads can be connected through relays, adding DR to the consumer's management.

In sum, the consumer can use the PV, energy storage battery, and DR to avoid consuming form the grid in times where energy is costly, and take advantage of reduced tariffs to charge the battery or satisfy consumption. In this way, the objective of the methodology is to minimize the energy bought from the grid to supply its consumption, and undertake the advantage of PV generation and DR to make the most of the flexibility that the battery system provides. The methodology considers an optimization process that runs side-by-side with the remaining resources, acting as a management system for the consumer to improve its energy efficiency and savings.

3 Scheduling Formulation

The mathematical formulation is an important part of the methodology and thus, it is presented in this section. In this paper, one intends to minimize the operation costs of a consumer given its interaction with the MN, which can be performed through a mixed-integer linear programming optimization. The optimization problem was modeled in MATLAB™/TOMSYM™ environment, and solved using CPLEX solver.

The DR curtailment cost in the objective function, is represented through weights $(P_{(c,t)}^{cut} \cdot W_{(c,t)}^{cut})$ showing the interests of the consumer for the load c in period t, and therefore affecting its operation if DR is applied. The objective function of the optimization problem, Eq. (1), shows the costs $(P_{(t)}^{grid\_in} \cdot C_{(t)}^{grid\_in})$ and revenues $(P_{(t)}^{grid\_out} \cdot C_{(t)}^{grid\_out})$ of the consumer's operation, i.e. when being supplied by the MN and when it injects power in the MN in each period t, respectively. The term, Δt, is equal to 4 and is needed to adjust consumption to the tariff at play, since consumption is in a 15-min basis, while the tariff is in an hourly basis.

$$\min EB = \sum_{t=1}^{T} \left[\left(P_{(t)}^{grid\_in} \cdot C_{(t)}^{grid\_in} - P_{(t)}^{grid\_out} \cdot C_{(t)}^{grid\_out} \right) \cdot \frac{1}{\Delta t} + \sum_{c=1}^{C} P_{(c,t)}^{cut} \cdot W_{(c,t)}^{cut} \right]$$

$$\begin{cases} P_{(t)}^{grid\_in} = P_{(t)}^{grid}, \ if \ P_{(t)}^{grid} > 0 \\ P_{(t)}^{grid\_out} = P_{(t)}^{grid}, \ if \ P_{(t)}^{grid} < 0 \end{cases} \quad \forall t \in \{1, \ldots, T\} \tag{1}$$

Equation (2) insures the balance between load and generation. As for the interaction with grid, one considers that when the energy is bought from the grid in period t, the variable $P_{(t)}^{grid}$ assumes positive values, otherwise, when the energy is sold to the MN, the same variable has negative values - Eq. (3).

$$\sum_{p=1}^{P} P_{(p,t)}^{PV} + P_{(t)}^{grid} + \sum_{c=1}^{C} P_{(c,t)}^{cut} + \sum_{st=1}^{ST} P_{(st,t)}^{dch} = P_{(t)}^{load} + \sum_{st=1}^{ST} P_{(st,t)}^{chg}, \quad \forall t \in \{1, \ldots, T\} \tag{2}$$

$$-P_{(t)}^{grid\max\_out} \le P_{(t)}^{grid} \le P_{(t)}^{grid\max\_in}, \quad \forall t \in \{1, \ldots, T\} \tag{3}$$

The flexibility provided by DR is an important part of the integration of DG, since it allows the load profile to be adjusted according to the output of generation. In this case, the proposed methodology considers the use of load shedding through relays incorporated in the PV inverter. Equation (4) represents the limits for the load shedding, $P_{(c,t)}^{cut}$, in the different loads connected to the relays. Equation (5) shows that when the relays are activated, the loads that are connected to them are shed. This is insured by the decision binary variable $X_{(c,t)}^{cut}$, for each of the relays.

$$0 \le P_{(c,t)}^{cut} \le P_{(c,t)}^{cut\max}, \quad \forall t \in \{1, \ldots, T\}, c \in \{1, \ldots, C\} \tag{4}$$

$$P_{(c,t)}^{cut} = P_{(c,t)}^{cut\max} \cdot X_{(c,t)}^{cut}, \ X_{(c,t)}^{cut} \in \{0, 1\}, \ \forall t \in \{1, \ldots, T\}, \ c \in \{1, \ldots, C\} \tag{5}$$

Moving on to the battery system, this is very useful in applications where there are time-of-use tariffs, per example, the battery can be charged during the less costly periods and discharged during the costlier periods to avoid a higher amount of energy bought from the MN. Similar to the generation units, the battery has operation capacity

($E^{stor}_{(t)}$) limits, Eq. (6), charge ($P^{chg}_{(t)}$) and discharge ($P^{dch}_{(t)}$) limits, Eqs. (7) and (8), respectively, in each period *t*. Equation (9) represents the impossibility of charging ($X^{chg}_{(t)}$) and discharging ($X^{dch}_{(t)}$) during the same period *t*. The parameter *ST*, represents the total number of batteries considered, which in this case, is only one. The battery system maintains a power balance within, thus Eq. (10) presents the balance between what comes in and out of the battery, and its state.

$$0 \leq E^{stor}_{(st,t)} \leq E^{stor\,\max}_{(st,t)}, \quad \forall t \in \{1,\ldots,T\}, st \in \{1,\ldots,ST\} \tag{6}$$

$$0 \leq P^{chg}_{(st,t)} \leq P^{chg\,\max}_{(st,t)} \cdot X^{chg}_{(st,t)},\ X^{chg}_{(st,t)} \in \{0,1\}, \quad \forall t \in \{1,\ldots,T\}, st \in \{1,\ldots,ST\} \tag{7}$$

$$0 \leq P^{dch}_{(st,t)} \leq P^{dch\,\max}_{(st,t)} \cdot X^{dch}_{(st,t)},\ X^{dch}_{(st,t)} \in \{0,1\}, \quad \forall t \in \{1,\ldots,T\},\ st \in \{1,\ldots,ST\} \tag{8}$$

$$X^{chg}_{(st,t)} + X^{dch}_{(st,t)} \leq 1, \quad \forall t \in \{1,\ldots,T\},\ st \in \{1,\ldots,ST\} \tag{9}$$

$$E^{stor}_{(st,t)} = E^{stor}_{(st,t-1)} + P^{chg}_{(st,t)} - P^{dch}_{(st,t)}, \quad \forall t \in \{1,\ldots,T\},\ st \in \{1,\ldots,ST\} \tag{10}$$

4 Case Study

The present paper addresses a prosumer located in a Portuguese network, and following its current legislation which allows small producers like consumers with local generation, not just use the energy produced to satisfy their own load necessities, but also sell it to the MN. The case study considers a system built of two PV systems and a battery, that belongs to a consumer, as illustrated in Fig. 1. The consumer has a supply power contract of 10.35 kVA with the MN characterized by time-of-use tariffs, namely, three different periods: peak, intermediate, and off-peak. Beyond the dynamic pricing, the consumer can inject energy into the MN until half of its contracted power, approximately, 5.1 kW. The prices applied to the consumer's operation with the grid are showed in Table 1. The prices shown are real values that a major supplier in Portugal offers to its clients.[1] This contributes to a more accurate study and methodology application, since real-life conditions are considered. In what concerns DR, the objective function considers weights defined by the consumer for the periods where is more acceptable and beneficial to use load flexibility, that in this case, is directly related with the dynamic pricing as when the energy is cheaper, less attractive is the DR. The amount obtained from the weights considered in the objective function is removed after the optimization problem since it doesn't represent an actual cost but rather a consumer's preference that influences the scheduling. Regarding the on-site generation and storage units, the PV system is composed by two inverters divided between the PV modules, having a maximum production of 7,5 and 2,5 kW. The battery is connected to

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[1] https://energia.edp.pt/particulares/energia/tarifarios.

Table 1. Prices of the different periods and contracted power.

	Energy (€/kWh)			Contracted power (€/day) - *DCP*
	Peak	Intermediate	Off-peak	
Buy from grid	0,3326	0,1681	0,0930	0,5120
Periods	10 h–13 h 19 h–21 h	08 h–10 h 13 h–19 h, 21 h–22 h	22 h–00 h 00 h–08 h	
Sell to grid	0,1659			–
DR weight	0	0,2	0,4	

the same inverter as the second PV (2,5 kW), being able to be charged from it, from the other PV system, and from the MN.

The inverter that holds the PV and battery system can perform the shed of up to three loads with incorporated relays. In case of insufficient PV production and/or energy stored in the battery, the loads connected to these relays can be shed to guarantee the energy balance in the inverter, opening a path for DR to support DG operation. In this case study, it is considered that the load of the dishwasher, air conditioning, and water heater can be shed, while the unknown load cannot (designated by “Others”). Figure 2 shows the discriminated load and PV generation forecast throughout the periods – 15-min intervals. Through Fig. 2, one can see a typical load profile with a peak of 11,5 kW, around 11:45 h.

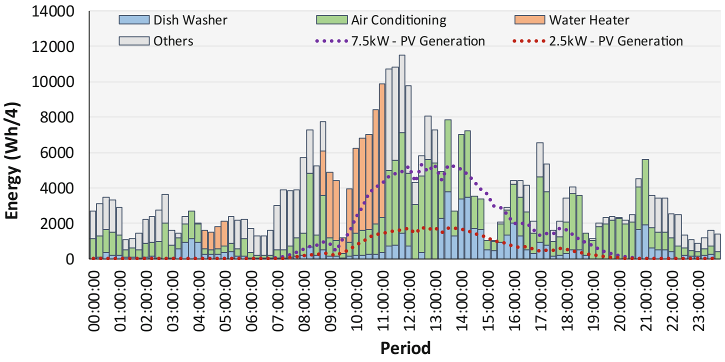

Fig. 2. Discriminated consumption by appliance.

5 Results

In the present section, one analyzes the results obtained from the implementation of the proposed methodology and respective case study. In Fig. 3 it is shown the resource’s scheduling obtained by the consumer and its interaction with the grid. As mentioned

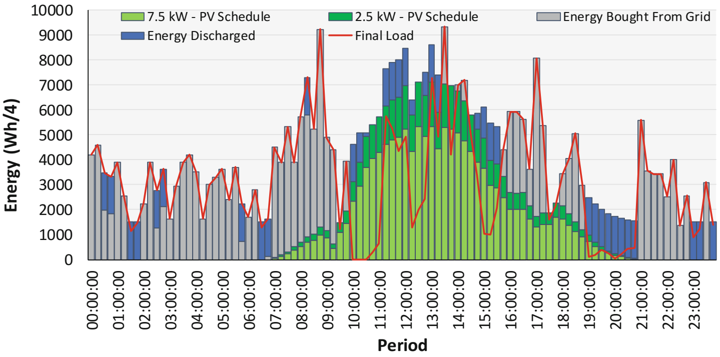

Fig. 3. Resources scheduling for the consumer.

before, the PV generation has the highest priority and thus is always scheduled. By Fig. 3, it is possible to observe that due to this condition the generation exceeds the consumption needs, and in this case, the energy surplus will either be used to charge the battery or sell to the grid. In this way, the consumer avoids buying energy from the grid to charge the battery and to meet consumption necessities. The above figure shows that the battery is mostly charged during the dawn, to be later discharged during the peak hours (10:00 to 13:00, and 19:00 to 21:00).

Also, as shown in Fig. 4, DR is applied during peak hours due to the contract's high tariff. The results obtained for the operation costs, show an improvement in terms of energy savings when the methodology is applied, as shown in Eq. (11), in comparison with the consumer being supplied always by the grid connection (normal operation of consumers).

$$EB_{New}^{Day} = DCP + \sum_{t=1}^{T} \left[\left(P_{(t)}^{grid\_in} \cdot C_{(t)}^{grid\_in} - P_{(t)}^{grid\_out} \cdot C_{(t)}^{grid\_out} \right) \cdot \frac{1}{\Delta t} \right], \quad (11)$$

$$\forall t \in \{1, \ldots, T\}$$

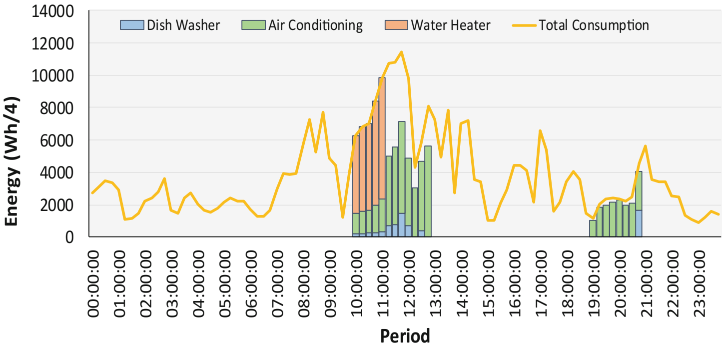

Fig. 4. DR actuation regarding the initial total consumption.

With the proposed methodology, the daily operation cost is 2,48 €, while in normal operation (without PV, battery and DR) it is 18,24 €. This means that, in this case study, energy savings could be achieved up to 86,4%, by implementing PV-battery system and adopting simple DR strategies.

6 Conclusions

The present paper addresses a methodology for the scheduling of hybrid systems composed of demand flexibility, PV and battery units, where the prosumer's electricity bill is minimized with a dynamic pricing contract. The proposed methodology represents a simple optimization problem that can considerably improve the consumer's energy savings, through an efficient use of resources and intelligent consumption strategies. Moreover, the application of this methodology, due to its formulation simplicity, is easily implemented as an executable in a system software, and run on a timely basis, while a monitoring infrastructure provides the needed data.

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