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Integration of Responsive Hybrid Loads into an Electrical System with High Penetration of Photovoltaic in Senegal

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Key words: PV penetration, demand response, cooking plate, excess green energy, unit commitment

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Abstract: Pursuing the objective of improving the photovoltaic penetration rate in an electric mix dominated by thermal energy, the integration of the demand response is solicited to absorb the fluctuations and intermittencies induced by the energy from PV. In the work presented in this study hybrid loads participate in the demand response, offering the advantage of targeting a household activity not yet considered in the load profile but also avoiding the report and rebound effects often seen in demand side management. It will be a question here of evaluating the capacity for these loads to absorb the energy surplus of origin PV whose quantity exceeds at certain time the demand coming from the conventional loads.

INTRODUCTION

Many studies have shown that it is possible to achieve a significant photovoltaic (PV) penetration rate, beyond the limits set for an electrical system that does not integrate a flexible energy management, in a realistic scenario with as another benefit the mobilization of a small amount of synchronous reserve and backup[1]. This situation is, however, accompanied by the presence of excess PV energy which is therefore unusable, by conventional loads, since, the demand on a global scale is already satisfied[2].

The objective of the work presented in this study is to direct this energy towards loads previously un-managed by the electrical system.

There are several ways to involve loads in a smart grid as described by Papavasiliou[3]. We will focus here on the model of direct coupling of loads to fluctuating and intermittent energy producers, in an improved version. This can be achieved by using an operator that adapts the inter-temporal energy demand of the responding loads to use the available renewable resource while minimizing its dependency on the backup generators of the system.

This study will describe the modeling of smart-grid type electrical system in order to involve hybrid loads able to consume this energy in a market evolving according to the presence or not of the surplus energy originated from photovoltaic. In the following, we will call it “Excess Green Energy (EGE)”.

MATERIALS AND METHODS

System model

Reminder of the fundamentals of the demand response and hypothesis: To address the variability of renewable energy supply through Demand Response (DR), three basic approaches are often used[3]:

- Centralized load distribution by the system operator
- Coupling renewable energy generation with a deferrable demand
- Price-elastic demand bids

In order to meet the objectives presented above while managing the associated constraints as well as the shortcomings noted on each of the main demand response models, hypothesis as to the choices that will be made are presented below.

We recall a few operating rules of the charges involved, so that, the producers, the network operator and the consumers find an interest to be a player of the smart-grid:

- Users must acquire this energy based on incentives
- The mode of consumption must be transparent for the user
- The network operator saves the costs related to the provision of the synchronous reserve
- The network must support the power flows induced by high penetration of the PV
- The overall load profile must not be modified in an unpredictable way because of the report and rebound effects often observed on the networks where the demand response is present[4]

We consider the possibility to have a cooking equipment in a hybrid form which could work under the EGE when this one is available and conversely it would switch to LPG mode in case of intermittence of the EGE without human intervention.

Another point mentioned limits the use of the network beyond the authorized flow limits due to the high penetration of the PV. Thus, in our scenario we will limit the aggregate maximum PV output to the same level as that observed during peak consumption.

Modeling unit commitment: In the studied system, we consider N production units connected to a single busbar serving a given aggregate load. The entry for each unit, indicated by F_i, represents the unit cost rate. The output of each unit, P_i, is the electrical power generated by this unit as shown in Fig. 1. The total cost of this system is of course the sum of the costs from each of these units. The essential constraint on the operation of this system is that the sum of the output power must be equal to the load demand.

Mathematically, this can be considered as an objective function, F_T, that is equal to the total cost of producing the indicated load as expressed in Eq. 1. The problem is to minimize F_T under the constraint that the sum of the power generated must be equal to the received load. We specify that all the transmission losses are neglected but the operating limits will be explicitly indicated during the formulation of the problem:

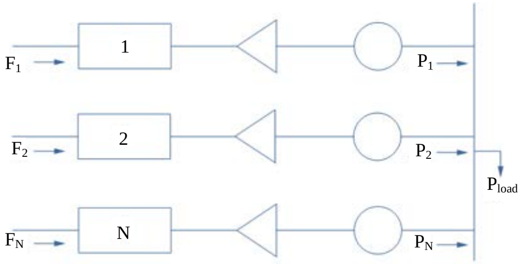

Fig. 1: Diagram of N units committed to satisfy the load P_{load}

$$F_T = F_1+F_2+F_3+, ..., F_N = \sum_{i=1}^{N} F_i(P_i) \tag{1}$$

The unit allocation model used in the suite is a customized version, from the one developed by Vladimir Stanojevic in March 2011 under MATLAB, based on[5-7]. We added the PV production prioritization as well as the output calculation of the "EGE" model. Particularly with the equations and conditions below:

$$\frac{dF_i}{dP_i} = \lambda \tag{2}$$

$$P_{i,\,min} \leq P_i \leq P_{i,\,max} \tag{3}$$

$$P_{loadTh} = P_{load} - P_{PV} \text{ if } (P_{load} - P_{PV}) \geq 0; \text{ else } 0 \tag{4}$$

$$\sum\nolimits_{i=1}^{N} P_i = P_{loadTh} \tag{5}$$

$$P_{eve} = P_{PV} - P_{load} \text{ if } (P_{load} - P_{PV}) \leq 0, \text{ else } 0 \tag{6}$$

Where:

λ = The incremental cost rate of producer i
P_{loadTh} = The power of the load satisfied by the thermal output
P_{eve} = The excess power from renewable sources

Case study: The model, thus, developed is subject to the case of Senegal national grid with a period of 72 h from june the 14th to the 16th of 2018, using real data and a simulation tool developed by Cisse *et al*.[8] with for each day a typical case. The first day is a working day of the week, the second day is a business day with significant cloud cover across the country and the third is a weekend day.

At the output of the model following a simulation, we obtain the list of the commitments of the units in steps of 1 h taking into account the constraints posed in the equations presented above. The PV surplus (EGE) is also evaluated over the entire period. His 72h profile is shown in Fig. 2.

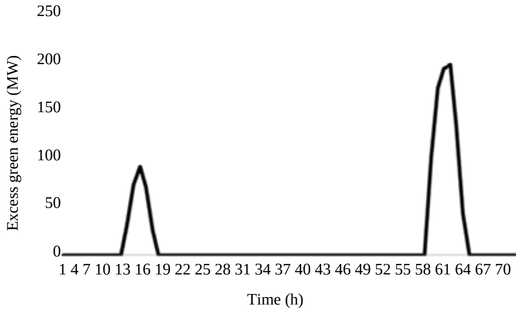

Fig. 2: Excess green energy profile after running unit commitment model for a period of 72 h

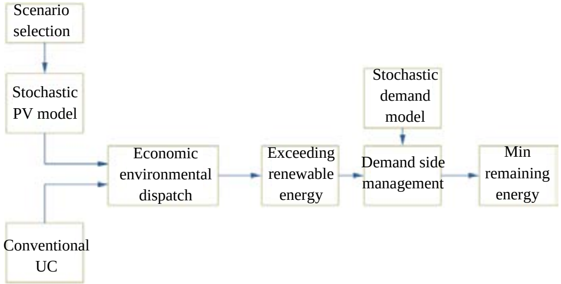

Fig. 3: Integrated DR Model with responsive loads

We can note that during the working days, with a sunshine broadly satisfying, the Green Surplus energy reaches levels below the 100 MW mark while the weekend following the same climatic conditions this energy is doubled. By cons with a cloudy sky in most of the territory, the green energy excess is nonexistent. This undistributed green energy will be used in the demand response model for consumption by responsive loads with the objective to minimize it as show in Fig. 3.

Modeling responsive hybrid loads: As we mentioned before, the target responsive load in this study in the residential sector is the cooktop which we recall has the advantage of being not yet considered in the overall load profile since more 95% of households use firewood, charcoal or LPG for cooking in Senegal. The LPG is used in the city at 80%[9].

Let's remember that an important principle that makes the load responsive is the fact that its erasure or change of setpoint is not or hardly felt by the user. This is the main reason why in this point, we are implementing a hybrid cooktop in the sense that it will be able to switch between the power source and the LPG source according to the conditions calculated by the DR market. This principle will also make it possible to avoid the report effects observed in the most well-known DR schemes, since the demand not satisfied by the EGE is not reported; it is immediately satisfied by the LPG source.

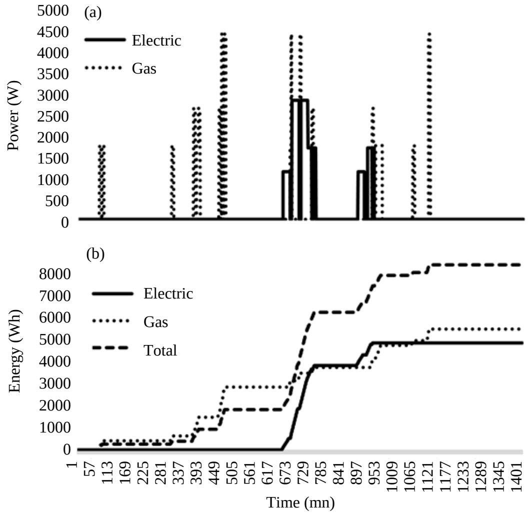

Fig. 4(a, b): Cooking equipment consumption related to EGE availability

The aggregator calculates the operations, determines the EGE and then exchanges with the pool of cooking plates for consumption with the objective of minimizing the amount of EGE remaining.

According to this operating principle, the plate model receives inputs and after processes. The inputs:

- The request: the user expressed a need to turn on a cooking plate
- The signal informing the plate of the availability of surplus green energy

The outputs: The state of the cooktop. Three values are possible, the first means that the plate is in operation and is supplied with gas, the second that means that the plate is in operation and is supplied with electricity and the last state that indicates that the plate is stationary. The power and energy consumed in gas mode and in electricity mode (Fig. 4).

Over a thousand simulations carried out, the total energy consumed per day for cooking varies varies in a range between 4 and 10 kWh which is close to the average consumption of a household per day is consistent, in the latter is 6 kWh[9].

We also note that the useful electrical energy used during the 24 h is about half of the total energy (electric+gas). This is due to the EGE which is mostly available during a short time but coincides with the greatest daily consumption, the mid-day meal preparation. The resulting model is thus ready to be integrated into the demand side management that will be developed later.

Market modeling: Once the unit commitment with PV considered has calculated the excess green energy, this one constitutes an input of the algorithm of the market in charge of the distribution of this energy to the various active loads in use. The different steps of the algorithm are described below.

If the available energy (EGE) is greater than the cumulative demand of the plates, then this one is satisfied and the rest will constitute the undistributed energy.

Otherwise the plates that are already operating in electric mode are satisfied first randomly, this to prevent untimely starts and to preserve equity between cooktops.

If the available energy can satisfy the demand of these cooking plates, the rest is transmitted to the plates that request it but which were not in electrical mode, randomly.

RESULTS AND DISCUSSION

In this part, we present the following elements of answer:

- The capacity of the hybrid hotplate fleet to absorb excess green energy as its extent correlates to the level of overall sunlight and load profile
- Jump in the penetration of the PV, thus, observed on the electric mix, taking into account the consumed EGE
- The environmental benefit in terms of avoided greenhouse gas emissions

Impact of the involvement of active loads on the use of EGE: We present in Fig. 5 the progression of the consumption of the EGE according to the number of plates that constitutes the fleet of active loads, during a sunny working day.

During a day with a low level of sunshine observed throughout the territory, we find that the EGE is zero which leads to a consumption of hybrid plates exclusively in gas.

On the other hand, for a holiday with a high level of sunshine, the EGE is evaluated in large quantities (Fig. 2) and its presence in the system induces a different behavior of the plates. The compaction of the curve of the energy used is observed starting from 200 thousand plates as shown in Fi. 5a and remains practically constant beyond. In addition, Fig. 5b indicates that from the same threshold the rate of use of the EGE is capped at 80%. Thus, in the scenario offering the most surplus green energy, we can finally retain that 20% of the EGE cannot be consumed by the hybrid cooking plates.

Evaluation of the level of PV penetration: In a context supported by the implication of the active loads in the context of a demand response, the scenario of a PV installation up to 800 MWp becomes realistic insofar as we have shown that the active loads can absorb a much of excess energy. In addition, the need for synchronous reserve to contain the fluctuations and intermittences of PV production becomes marginal.

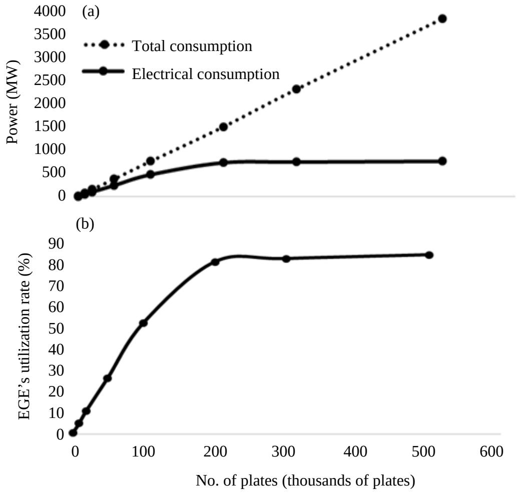

Fig. 5(a, b): Progression of power and utilization rate of EGE related to the number of cooking equipment

Table 1: Penetration rate for scenario with 800 MWp PV

Sector	Power penetration (%)	Energy participation rate (%)
Thermic	94	41
Hydro electric	1067	534
Total production	77	35

At such a level of penetration in installed power, we indicate the correlations with respect to the electric mix in Table 1.

For 77% power penetration of PV, energy participation is estimated at 35% of all production. The load profile becomes meanwhile change mid-day due to the presence of new charges that are the hybrid plates.

Assessment of environmental benefits: Environmental benefits are assessed at two different levels directly impacted. These include:

- The production of thermal energy avoided by the installation of a large photovoltaic capacity on the one hand but also
- Decrease in the volume of LPG gas used in households due to the presence of hybrid cooktops

By reducing the PV energy penetration rate to 35% over the study period, thermal energy production dropped by almost 42%, or nearly 31% of avoided CO_2 emissions if we rely on the study of NH Sark *et al*.[10].

As for the consumption of the hybrid plate, part of the EGE consumed will have prevented the use of LPG up to 48% (for days with a high presence of excess green energy), i.e., almost half of their consumption if we consider the optimal number of plates involved.

CONCLUSION

This work was done in the perspective of improving the penetration rate of PV on the electric mix by providing a flexible demand.

By fixing a level of penetration that could generally be supported by the electrical grid, we have intermittently observed an energy unused by the system which has led to imply needs not yet or almost not supported by the electrical system in the residential sector. It is in this context that hybrid cooktops (with electrical source and LPG) have been used, offering the additional advantage of avoiding the effects of bounce back often observed in networks where the DR is implemented. In the scenario with the largest amount of PV energy not used by the conventional system, nearly 80% of this energy could be captured by the hybrid plate pool. This improves the penetration rate of the PV, so to be evaluated at 35% for a day of strong sunshine. A portion of this excess green energy up to 50% replaces the energy consumed for cooking in a perimeter where LPG was used.

In addition, despite the involvement of these active loads to absorb the EGE, the rate of its use remains capped between 70 and 80% depending on the climatic conditions which reflects the existence of nearly 20-30% of this energy that was left unused by the system. This observation leads to a new work in which hybrid plate coupled with water heater is envisaged, this latter having the inherent ability to store energy after its conversion into heat before use.

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