ENERGY MANAGEMENT SYSTEM WITH DEMAND RESPONSE FOR SOLAR HOME

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Abstract

In order to reduce the energy consumption and the environmental footprint of the residential sector, the use of renewable energy sources seems to be an interesting option. However, the intermittent nature of these sources necessitates the installation of a Solar Home Energy Management System (SHEMS) that would ensure both the management of the energy flows and the optimization of the energy demand satisfaction through on-site photovoltaic production of electricity. Regarding the relative incompatibility of photovoltaic production and residential energy consumption profiles, it has been practically demonstrated that the integration of a demand response strategy in the SHEMS system made it possible to adapt the consumption profile to the photovoltaic production profile by shifting the running of the controllable loads to periods of high energy production. This demand management (DR) increases the direct consumption of the PV production by 22%, reduces the energy exchanges with the network and improves, at the same time, the satisfaction rate of the demand by 14%.

Keywords: Home Energy Management System, Renewable Energy, Solar home, Demand Response, Appliance scheduling

I. Introduction

In an energy context marked by an ever-increasing energy demand and a continuously rising greenhouse gas (GHG) emissions causing global warming of the earth, a significant reduction in energy consumption is necessary. According to [IV],
the residential sector consumption has increased significantly in the recent years because of the high growing number of electrical and household appliances that are used in homes. The use of the Renewable Energy Sources (RES) seems to be a relevant solution that can, at the same time, resolve the domestic and environmental energy problems encountered with the use of conventional energy sources in the building sector. However, the intermittency of these RES should be managed [I], [XIII]. For this, it is necessary to design and mount a Solar Home Energy Management System (SHEMS) that manages the energy production, the energy consumption and minimizes energy costs [VII].

Several studies have been reported in the literature on Home Energy Management Systems (HEMS) [XVIII], [XII], [XI]. The optimization of domestic energy consumption using a Power Line Communication (PLC) to transfer the consumption information has been treated by [XIX]. An intelligent HEMS based on Home Energy Grid (HEG) technology that remotely monitors and controls home appliances has been suggested by [VI]. In [IX], the authors proposed a smart HEMS green module that controls and compares the energy consumption of household appliances of the same type in order to reduce the total domestic energy consumption. In [VIII] and [XIV], the energy management systems have been studied to improve the energy consumption in smart homes by providing automation systems to control the residential loads. Demand Management Strategies (DMS) have been used in the HEMS to reduce the energy costs by changing the shape of the consumption profile through shifting of the demand peaks from high demand periods to low demand periods of the day by several authors [XV], [III].

In this paper, a devoted HEMS architecture for a solar home based on radio-controlled outlets and a Solar Energy Gateway (SEG) is presented. The radio-controlled sockets collect the energy consumption data of the household appliances and communicate them to the Home Manager via a Bluetooth connection. The photovoltaic production data are then transmitted to the SHEMS via the SEG. The SHEMS records and processes these data to optimize the use of the locally produced photovoltaic energy at the solar house. In addition to that, programmable devices can be automatically shifted in order to consume the excess of the photovoltaic energy production.

II. Architecture of the Proposed Solar Home Energy Management System

Structure of the SHEMS

Fig. 1 shows the overview of the SHEMS used in the low energy consumption solar house installed at UDES in Bou Ismail. The SHEMS system is intended to manage the energy production, the energy storage and the energy consumption. The energy production is guaranteed by a 3.2 kWp photovoltaic generator and the energy storage is insured by a lead acid battery bank with a total capacity of 12kWh. This type of batteries is widely used in photovoltaic applications because of its low cost [II]. The battery inverter, which is equipped with a bidirectional bus (AC / DC and DC / AC), is used to charge the batteries and to supply electrical energy to the loads. This battery inverter is connected to the Home
Manager via a RS-485 serial port. The loads management (appliances, lamps, ..) is performed by the Home Manager via the Energy Meter and the radio-controlled sockets (smart socket). They periodically, communicate the measured values to the Home Manager via a Bluetooth communication. All the energy information related to the PV plant, the grid and the battery bank are sent to the Home Manager to be used, then, for energy flow management.

![Architecture of the Solar Home Energy Management System (SHEMS)](image)

**Fig. 1:** Architecture of the Solar Home Energy Management System (SHEMS)

**The Home Manager**

- The Home Manager receives information about the electricity demand over a given period of time to generate the home load profile. In addition to that, it produces a PV production profile by using the radiometric and meteorological predictions of the site. In fact, the objective is to establish matching between the production and the consumption profiles in order to satisfy the entire home energy demand by the on-site solar energy system.

- The Home Manager deals with a given situation, based on the principle of the management of the demand of energy of the house or the Demand Response (DR) defined in the paragraph (II.3). For example, in a period of low PV production, the operating period of the controllable loads (the washing machine, the dishwasher, and the air conditioner) can be shifted to periods where the solar power generation is high. The scheduling of the loads is done automatically by the Home Manager according to the order of priority of the loads.

**Integration of the Demand Response to the SHEMS**

- The Demand Response (DR) is defined as the change in users' electricity consumption profile compared to their usual consumption in order to respond with a cost effective manner to the change in the electricity rate [V] by adjusting the instantaneous level of electricity consumption [XVI]. The DR is generally used (in Europe and in the USA) in photovoltaic installations connected to the network where...
In this article, the focus was on the potential for improving the management of the distribution of photovoltaic electricity and for reducing the dependency of the public grid. This is determined by programming the operation of household appliances through an SHEMS.

In general, the loads available in a house are classified into two categories: controllable loads and uncontrollable (critical) loads. The controllable loads can be controlled individually by the SHEMS according to the consumer's preferences through radio-controlled sockets set for each appliance. The critical loads are, for example, lamps, the refrigerator, the TV and the stove which are uncontrollable. In this study, the loads were ranked, as shown in Table I, in order of priority of use.

**Demand Response Strategy**

The Demand Response (DR) strategy applied in the studied system is based on the time shift of loads from peak demand periods to off-peak demand periods. The role of the SHEMS, in this case, is to plan the operation of the household loads throughout the day. It shifts the time of operation of the 'reportable' devices in such a manner to optimize the energy consumption from the local PV production. To do this, the user must provide the SHEMS with the list of loads to be operated with priorities prefixed 24 hours in advance. Using the necessary information (appliances consumption and weather forecast) provided by the inverters, the radio-controlled sockets and the smart meter, the SHEMS generates the PV production forecasts and the total consumption profile of the house. After processing all the input data, the SHEMS plans the operation of the different loads according to their priorities and available energy. It must be noted that the application of the DR does not reduce the consumption of the house, but favors the consumption of the photovoltaic energy to get rid of the network.

**Experimental Setup**

This part describes the implementation of the various components of the SHEMS system in the solar house and the operation of this system with and without load scheduling. The SHEMS system comprises several elements: The Home

| Priority | Appliance | Electricity consumption (kWh/day) | Type               |
|----------|-----------|----------------------------------|--------------------|
| 1        | Lights/ Refrigerator/ Computer/ Stove | 7.35                | Non Controllable   |
| 2        | Air conditioner | 7.36                | Controllable       |
| 3        | Dishwashers  | 0.92                 | Controllable       |
| 4        | Clothes washer | 1.89                | Controllable       |
| 5        | Other appliances | 1.04                | Non Controllable   |
manager, the Energy Meter, the Smart Sockets and the SEG. The house is equipped with household appliances, including a refrigerator, TV, electric oven, air conditioner, washing machine, dishwasher and lamps.

In order to evaluate the performance of the SHEMS established in this work, a comparison of the demand satisfaction rate with and without using a load management was performed. For this purpose, the PV production and the daily consumption for both types of management (with DR strategy and without DR) has been conducted. Two representative days, namely, a day with free behavior of the users and another day with programming shift able loads such as the washing machine, the dish washer and the air conditioner were used to evaluate the contribution of the demand response on the improvement of the energy management of the solar house.

III. Results Analysis

The goal of the SHEMS system is to manage the energy flows in the solar house in order to satisfy the energy demand of the home. The integration of the DR into the solar house by planning the devices is done for minimizing the peak consumption and thereby improve the behavior energy of the house. The results of the two energy management scenarios (with and without the DR technique) are presented in the following:

Energy Flow Management in the House without DR Strategy

In order to test the performance of the SHEMS, a series of measurements of electrical and radiometric parameters were performed in the solar house during the period June - July 2019, which represents the hottest period of the year for the site considered, which requires intensive use of air conditioning. The daily consumption, during this period, varies between 14 and 18 kWh and the photovoltaic production, which is very favorable, reaches around 17,614 kWh / day.

Fig. 2 displays the production and the consumption energy flows during the day of June 1, 2019. Many peaks consumption were recorded during this day at around 7. am, 10. am, noon, 6. Pm. and 9. pm.

During the morning (between 1. am and 10. am), the consumption is ensured by the batteries which are initially charged at 45% of their rated load. From 10am, the photovoltaic production is able to satisfy, at the same time, the home energy demand and charge the batteries. In the case considered, the batteries can only be charged by the PV field.

From 17:45, the home energy needs exceeds the PV production, then the batteries switch to the discharge mode in order to compensate the deficit caused by the low PV production. The batteries continue to discharge until they reach their maximum discharge depth which is set to 20% of their nominal capacity, then the electricity network is solicited to meet the energy demand of the house until the PV production is sufficient to satisfy the energy demand. For the case considered, the energy quantity withdrawn from the grid is 1.9 kWh for the case considered. The satisfaction rate of the needs of the home reaches 81.50% only by using the storage.
In this section, the influence of the Demand Response (DR) strategy on reducing the consumption peaks during the night time periods is treated. In fact, The management of these consumption rates is done by shifting the reportable loads using the SHEMS system. The three loads concerned by the shift by the system manager are: the washing machine, the dishwasher and the air conditioner. The startup of these charges depends on the quantity of energy available and the order of priority order indicated in Table I.

The load profiles of these three controllable devices are shown in fig. 3, where (a) indicates the power consumption of the washing machine, at a temperature of 40 °C and a rotational speed of 1000 rpm, (b) the dishwasher, at 40°C in economy mode and (c) the air conditioner at a temperature of 25 °C. Moreover, important loads such as lighting, refrigerator, TV and stove are considered as being able to be activated at any time throughout the day.

The period and duration of operation of the three controllable devices are shown in Table II. Considering the PV production profile, it appears that it is preferable to put them off before 16:00. It should be noted, however, that the air conditioner has two operating periods, 13:00 - 16:00 and 20:00 - 22:00. During this last period the consumption of the air conditioner is ensured by the batteries.

### Table 2: Appliances starting and ending times for minimizing peak load

| Appliance       | Start time | End time  |
|-----------------|------------|-----------|
| Clothes washer  | 10:00 am   | 11:05 am  |
| Dishwasher      | 12:45 am   | 13:30 am  |
| Air conditioner | 12:00 am   | 15:00 am  |
**Fig. 3:** ENERGY CONSUMPTION OF THE CONTROLLABLE LOADS FOR A SOLAR HOUSE

Fig. 4 shows the power flows in the PV system during the day of June 2, 2019 when using the DR. The SHEMS detects through the radiometric and the meteorological forecasts the surplus of energy production and immediately actuates the reportable charges selected by the manager of the system. The batteries are initially discharged (minimum charge level SOC = 20%). The use of the DR strategy maximizes the energy consumption from photovoltaic production, which passes from 14.04kWh to 16.63kWh that increases the satisfaction rate by 14%.

**Fig. 4:** Power flows for measured experimental day with DR activated
Fig. 5 shows that the application of the DR modifies the overall energy consumption profile of the solar house by shifting the carry-over charges from the peak period to the off peak periods which coincides with the peak of the photovoltaic production. Table III shows the values of the energy parameters for the two days considered.

### Table 3: Energy variables results

| Energy variables          | Day 1: Without DR | Day 2: With DR |
|---------------------------|-------------------|----------------|
| PV production (kWh)       | 17.614            | 16.635         |
| Load consumption (kWh)   | 17.227            | 16.534         |
| Grid exchange (kWh)       |                   |                |
| Imported                  | 1.912             | 1.178          |
| Injected                  | 3.874             | 0              |
| Energy demand satisfaction (%) | 81.50            | 96             |

**Fig. 5:** Consumption profile of the solar house with and without DR strategy

**Demand Satisfaction Improvement**

The fig. 6 shows the evolution of the rate of satisfaction of the consumption of the loads in the solar home with and without the application of the DR according to the state of charge of the battery bank (SOC). It should be noted that for a SOC <30% the satisfaction of the energy demand without using the DR strategy does not exceed 48% because of the non activation of the controllable loads initially planned from 6 pm. With the use of DR a 100% demand satisfaction rate is achieved without using the batteries. When the battery bank reaches a SOC of 50%, the satisfaction of the energy needs passes, while using the DR, from 80% to 100% thus reducing the use of 2kWh of storage. The application of the DR could help in reducing the size of the battery bank.
IV. Conclusion

In this paper, three aspects of residential PV systems have been addressed: a) the architecture of a SHEMS controller that considers both power consumption and power generation. b) the flow of energy in the house using only energy storage. c) the combination of storage and load shifting. It was found that the proposed modular architecture improves the energy management in a solar home by optimizing the consumption of locally produced PV energy. Furthermore, using the storage increases the consumption of the energy produced by the local source and decreases the injection into the network. Reducing or smoothing the consumption peaks requires the loads shifting at noon when the PV production is at its maximum. Applying the DR increases the load demand satisfaction by 14% when compared to the case where only the storage is used. The combination of the storage and the DR have permitted energy savings and significant network relief. The experiments carried out were limited to two days. Future work will focus on an annual monitoring of solar house energy management using the SHEMS coupled with the DR strategy for different consumption and production scenarios.

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