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Predictive demand side management of a residential house under intermittent primary energy source conditions

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ABSTRACT

This paper targets the process of optimizing the operation of a PV-battery backup system under intermittent grid electricity supply. A predictive scheduling layer is developed as a part of a complete load management process. The main objective of the study is to ensure a permanent power supply for a high energy consuming residential application. The control algorithm plans the activation of predictable loads 24 h ahead through compromising between a decrease in the resulting discomfort levels and the conservation of a high autonomy of the system. The strength of the developed control lies in ensuring the complete coordination between all the components of the installation: the grid, PV panels, battery storage, and the load demand. No loss of power supply is allowed during the day and realistic and technical constraints are applied. The demand side management program is formulated as a multi-objective optimization algorithm solved using the Non-dominated Sorting Genetic Algorithm (NSGA-II) technique. A fuzzy logic decision maker is developed for an automatic trade-off process implementing the residents' preferences. The simulation results show excellent performance and flexibility of the proposed algorithm. The benefits of the load management are proved to have a great impact on the backup installation sizing, which leads to notable reduction of its price.

1. Introduction

Several developing countries suffer from regular and frequent grid energy blackouts, thus photovoltaic (PV) based backup systems are being used to fulfill the energy deficit during electricity cut-off periods [1,2]. Under such conditions, the primary concern is to maintain a permanent electricity supply. Given the long blackout periods and the unreliable nature of the solar energy, applying a Demand Side Management (DSM) is of great interest when coupled with the PV-Battery backup system [2]. With the ongoing development of smart grid concepts and sustainable energy technologies, DSM studies for residential applications have been emerging rapidly. The concept of load management consists in modifying the load profile of a residence in a way that serves best the objectives of the study. The DSM problem was treated differently in the literature according to the installed system, available resources, and main objectives. The most popular management objectives tackle the issue of energy price reduction and peak load shaving procedures while maintaining high comfort levels of the users [3,4]. The main difference between the various studies lies in the system structure and the techniques used to solve the problem. The control complexity increases with the number of involved components in the application. Topologies vary from relying solely on the grid, to more complicated installations involving renewable energy resources and energy storage devices. Load management programs have been applied to residential applications where the grid is the only energy supply source [5–8]. In [5] the load management is formulated as a Multi-Objective Optimization (MOO) problem aiming at reducing the energy purchase cost and the discomfort levels. A customised Non dominated Sorting Genetic Algorithm (NSGA-II) was applied to find the optimal solution. A Mixed Integer Non linear Programming (MINLP) optimization under time of use electricity prices and considering offered incentives to the user is applied in [6]. The main inconvenience of the algorithm is that it does not offer great flexibility to the user who has a restrictive choice to only favor his own convenience over the price reduction or vice versa. Other studies consider the same system topology, but focus on a single load: for instance the Heating, Ventilation and Air Conditioning (HVAC) [8,9] or water

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Nomenclature

Acronyms

HVAC	Heating, Ventilation and Air Conditioning
NSGA	Non-dominated Sorting Genetic Algorithm
PV	Photovoltaic
SEWH	Solar Electric Water Heater

Symbols

η_{ch}	efficiency of the charger
η_{inv}	efficiency of the inverter
σ	self discharging rate of the batteries
A_n	normalized autonomy of the system
E_{AC-L}	energy extracted by the load from the AC bus
$E_{batt-AC}$	energy injected by the battery bank to feed the load
E_{bmax}	maximum allowable energy in the battery bank
E_{bmin}	minimum allowable energy in the battery bank
$E_b(k)$	energy in the battery bank at step time k
E_{G-AC}	energy injected by the grid to the AC bus of the house
E_{G-Batt}	energy used from the grid to charge the battery bank
E_{Gc}	the constrained amount of energy allowed to be injected from the grid to the battery bank
E_L	energy extracted by the load
E_{PV-AC}	energy from the PV panels to feed the load
$E_{PV-batt}$	energy used from the PV panels to charge the battery bank
E_{PV-Inv}	DC energy supplied by the PV to the inverter
E_{PV}	energy generated by the PV panels
i	index of the considered end-user service
$i_{chr}(A)$	the electrical current extracted from the charger
k	step time of the energy flow computation
n_{HVAC}	number of decision variables to control the HVAC
n_{SEWH}	number of decision variables to control the SEWH
n_{WM}	number of decision variables to control the WM
n_{bat}	number of batteries
n_{cyc}	number of considered cycles for the permanent services reference variations
nb_{AC}	number of operating air conditioning units
P_{Lp}	maximum power extracted by the loads during the considered step time
P_{max}	maximum allowable power to be extracted from the grid, determined according to the main breaker size of the property
$t(i)$	end time of the considered end-user service
T_{HGA}	hot water reference temperature determined by the NSGA-II
T_H	hot water temperature inside the water tank
T_{indoor}	indoor ambient air temperature
T_{inGA}	indoor reference ambient air temperature determined by the NSGA-II
T_{in}	inlet water temperature
$T_{maxindoor}$	maximal allowable indoor reference temperature (28 °C)
$t_{max}(i)$	user defined upper bound of the end-user service activation time
T_{mean}	mean indoor temperature in a step time
$T_{minindoor}$	minimal allowable indoor reference temperature (20 °C)
$t_{min}(i)$	user defined lower bound of the end-user service activation time
$T_{optindoor}$	optimal indoor air temperature (22 °C)
$t_{opt}(i)$	user defined optimal end-user service activation time
$T_{outdoor}$	outdoor ambient air temperature
v_{bat}	battery bank voltage
W_d	average hourly hot water consumption

heaters [10]. More complicated installations consider the addition of energy storage techniques but have the same goal of reducing the energy bill [11]. Adding PV panels to the mix introduces other challenges to the management process. Researches as in [12,13] achieve a good coordination between the grid energy, PV power production, and the battery storage system, but exclude the energy demand. Other system configurations consist of applying DSM to standalone PV-battery systems. In [14] the initial economy of the homeowner in a developing country is taken into account. The study applies a load management program to reduce peak loads and therefore reduce the sizing of the inverter to match the capabilities of a medium income customer. The standalone PV system is extended in [15] in order to integrate the buying/selling electricity process from the grid. The developed scheduling aims at minimizing the energy costs and reducing the inconvenience of electrical and thermal loads to the users.

In this paper, a novel system topology is adopted along with objectives that differ from those popular in the literature. More components are involved in the energy mix: the grid, PV panels, battery storage and the required load. Therefore, a higher complexity is encountered for establishing a well-performing and reliable DSM program. One great challenge to the control algorithm is achieving an optimal coordination between the multiple components of the system. A PV-battery backup system is installed for a high energy consuming residential application. Following a load classification, the DSM is divided to two main layers: the scheduling and the real-time layers. This paper develops extensively the former layer. The DSM modifies the load profile of the house to maintain the desired comfort levels and ensure a reliable system that provides the residents with permanent power supply. The proposed control strategy takes into consideration realistic and technical constraints associated with each component of the installation as the contractual grid power threshold. An automatic trade-off procedure is achieved by applying a Fuzzy logic Decision Maker (FDM) which offers great flexibility to the user by allowing him to implement his preferences regarding the device priorities and autonomy level. A load priority classification can be done favoring a device over the other according to the residents' needs during the day. Furthermore, the proposed DSM is highly adaptable to the applied conditions as the occupancy hours, hot water demand, solar and blackout data.

Simulation results proved that the developed scheduling layer offers excellent performance and flexibility under various conditions. It manages to optimize the operation of each component of the installation, make great use of the energy storage capacities of the considered thermal loads, and respect all the imposed constraints. Moreover, the study suggests that the applied DSM can also lead to a high price reduction of the backup system that can reach 14,500€ over the 20 year lifetime of the system.

The remainder of the paper will be divided as follows: Section 2 explains the operation of the backup system and computes the energy flow between its various components; Section 3 describes the proposed DSM procedure; Section 4 details the control algorithm and formulates the optimization problem; Section 5 shows the simulation results of the control algorithm; Section 6 states the main conclusions and contributions of the study.

2. Backup system operation

The installed PV-Battery backup system works in conjunction with the grid. The concept of the backup system and the mandatory realistic constraints to be taken into account are extensively explained in [2].

Fig. 1 plots the three main operation scenarios and the energy flow of the PV-battery backup system. There are two main operation modes of the backup: when the grid power is available, and