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Technical note

Priority load control algorithm for optimal energy management in stand-alone photovoltaic systems

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ABSTRACT

In stand-alone PV System facilities no grid connection exists, therefore the solar generator and battery bank have to be carefully sized in order to supply the energy demand for a given period of time. Batteries are considered as a weak component of the system, comprising an important part of the total cost and are usually replaced one or two times during PV system lifetime. A priority load control algorithm has been developed in order to gain an optimal energy management over system loads and the battery storage, and therefore provides a better energy management efficiency and guarantee the energy supply for critical loads. This will increase the reliability of the system and the end-user satisfaction. This article describes a stand-alone PV system model used for the development of a priority load control algorithm and explains and implements the algorithm. The results of several test scenario simulations are shown and discussed.

1. Introduction

Electricity generation based on renewable sources has become an important topic today, driven by the increase of costs of fossil fuels and the concern about reducing CO_2 emissions to mitigate climate change. Photovoltaic (PV) solar energy is one of the most promising alternative energy sources, and thanks to a drop in prices in recent years, it is becoming economically and technical feasible even for domestic use [1,2]. However, Solar PV systems are relative expensive, especially on stand-alone PV (SAPV) systems which need an energy storage besides other PV system components.

In SAPV facilities no grid connection exists, the system is designed to supply enough energy to satisfy the energy demand for a given period of time. To accomplish that purpose, we have to carefully size the solar generator and the battery bank. Batteries are considered as one weak component of the system [3], comprising an important part of the total cost [4]. Optimal control over system loads and the battery storage can be employed to improve the payback period, to get a better energy management efficiency and reduce the size of PV system [5,6]. This task can be achieved using priority load control. Furthermore, with this type of control, the energy for critical loads can be guaranteed, given reliability to PV system.

About priority load control, different approaches have been taken so far. Groumpos et al. [7] and Khouzam and Khouzam [8] developed a load management strategy in SAPV system where the loads were classified into four general categories depending on their priority (convenient, essential, critical, and emergency). A variable priority was given to the battery bank dependent on the state of charge (SOC). The problem is mathematically formulated taking into account the priorities, and the optimal solution is obtained through dynamic programming techniques.

Groumpos and Papegeorgiou [6] proposed an optimal load management strategy based on three general load classification: the first category is the operational classification, which divides the load depending of voltage source: DC or AC. The second category is the system classification, which consists in classifying the load as uncontrollable, controllable or semi-controllable. The third category is the priority classification, which uses four priority levels: useful, essential, critical, and emergency load. In this method they use the controllable load to adjust the general load curve, in order to reduce the battery bank size. This improves the total life-cycle cost of the system, protects the battery bank and the priority of the loads is observed. Venayagamoorthy and Welch [9,10], worked on an energy dispatcher, which uses neural networks and fuzzy logic. The objectives are to optimize the energy supply, prioritizing

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Nomenclature

ΔT	temperature difference between battery temperature and 25 C
η_B	battery Faraday efficiency (V)
η_{inv}	inverter efficiency
τ	time constant for battery gassing process (h)
SOC	battery state of charge
SOC_{min}	battery bank minimum state of charge
a_1	logic signal from priority control algorithm
a_2	logic signal from load schedule
C	battery capacity (Ah)
C_{10}	battery nominal capacity at 10 h discharge rate (Ah)
e	electron charge (1.602×10^{-19}C)
E_B	battery bank available energy (Wh)
E_{ij}	energy required by load j of priority i in a specific period of time (Wh)
E_{pv}	PV module array output energy (Wh)
E_{ucL}	energy required for uncontrollable loads (Wh)
I	PV cell current (A)
I_0	solar cell dark current (A)
I_B	battery current (A)
I_G	PV generator current (A)
I_L	solar cell photogenerated current (A)
I_{10}	current needed to discharge a battery bank in 10 h (A)
I_{AC}	inverter AC current (A)
I_{DC}	inverter DC current (A)
I_{SCG}	PV generator short circuit current (A)
I_{SC}	PV cell short-circuit current (A)
k	Boltzmann's constant 1.381×10^{-23} J K^{-1}
K_1	constant value for V_{MPP} calculation
LLP	loss of load probability
m	ideality factor of PV cell ($1 \leq m \leq 2$)
N_S	number of PV modules in series
P_{ij}	average power required by a load j of priority i in a specific period of time (W)
Q	battery charge store at each Δt (Ah)
Q_{sc}	amount of current entering a battery when gassing begins (Ah)
R_B	weighted value associated with the battery bank operation
R_P	solar cell shunt resistance (Ω)
R_S	solar cell series resistance (Ω)
R_{ij}	weighted value associated with operating load j of priority i
r_{ij}	priority unit value associated with load j of priority $r = i$
R_L	load resistance (Ω)
R_{SG}	PV generator series resistance (Ω)
T	absolute temperature (K)
V	PV cell voltage (V)
V_B	battery voltage (V)
V_g	battery gassing voltage (V)
V_{AC}	inverter AC voltage (V)
V_{DC}	inverter DC voltage (V)
V_{fc}	battery final charge voltage (V)
V_G	PV generator voltage (V)
V_{mpp}	maximum power point voltage (V)
V_{OCG}	PV generator open circuit voltage (V)
V_{OC}	PV open-circuit voltage (V)
X_B	proportion of Δt to charge the battery bank
X_{ij}	proportion of Δt to operate load j of priority i

the critical loads and trying to keep the batteries state of charge as high as possible.

Predictive load management has also been developed. For example, Lujano-Rojas et al. [11] takes load parameters to predict load working time: the earliest hour at which a load must start its operation, the latest hour at which it must end its operation, the duration of the operation, the possible hour at which a load will start its operation, the power required, and the period of management. Therefore, the load management consists of making forecasts of the renewable energy source and using these predictions, it is possible to set the hour at which the appliance will start its operation for minimizing the energy supplied by the controllable power sources (like battery bank, diesel generator, or both).

Some of the previously cited works can only discern one priority level (priority or non-priority) [9,10]. Others, capable of handling multiple priority levels, have less precision in the energy estimation for PB-acid batteries [7,8].

Taking in account the previous review, we proposed a priority load control algorithm based on Khouzam and Khouzam's work [8]. We preferred to use a non-predictive approach because it would be a simpler system for a field implementation. Our approach includes an improvement on the energy estimation because battery available energy is calculated based on specific Pb-acid battery parameters equations, providing a better performance of the algorithm. Non-controllable loads are included in the algorithm, which extends it to be used in mixed scenarios with controllable and non-controllable loads.

This paper is organized as follows: in Section 2, we provide a description of the SAPV facility that provides our experimental data. In Section 3, we explain the all SAPV system modelling. In Section 4,we carefully detail the priority load control algorithm. We illustrate the operations of the priority load control algorithm through different cases studies in Section 5, and show the results on Section 6. In the final section, we draw the conclusions of the paper.

2. Stand-alone photovoltaic facility description and experimental dataset

The experimental data (irradiance, ambient temperature) and the components modelled on this paper, are part of a SAPV system located at the University of Murcia, Espinardo Campus. This facility started to operate on March 2003, and its purpose is to feed part of the lighting system of the Animal Service Laboratory. This lighting system is a constant load over 24 h and the energy required to work is 13.776 kWh per day [12].

A monitoring system was installed on 2007 to measure and record meteorological data (global and diffuse horizontal radiation, global tilted radiation and cell and ambient temperatures) and electrical variables (DC generated current and voltage, and DC & AC consumed voltage and current). The sample time of monitoring system is 5 min, and all the data that is measured is stored in a data base. A web-site has also been developed to present the behaviour of the facility and the research projects carried on using the system as an experimental test bench. The web allows the public to follow its performance on-line [13].

3. System modelling

A complete SAPV system model has been implemented on Matlab/Simulink software. Each component has been modelled in a