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Strategy of management of storage systems integrated with photovoltaic systems for mitigating the impact on LV distribution network

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ABSTRACT

This article presents an integrated storage management strategy with photovoltaic systems connected to the grid, to provide voltage regulation and losses reduction in the low voltage feeder, minimising the power supplied by the network upstream of the main transformer. A new control algorithm for battery energy storage systems (BESS) is presented embedding as a battery management algorithm for charging and discharging process. The charging of the storage system is defined by the optimization of the α_k coefficient to establish the value of charging threshold power, in a distributed manner, to maximise the use of photovoltaic systems. The discharging process occurs by a given σ coefficient. A standard network model from CIGRE was used for the validation of the management strategy. It was modified with real profiles of load and irradiance with a minute resolution to adapt it to the using of the quasi-static load flow in MATLAB/Simulink. As a result, by integrating 67% of PV along with 442 kWh of BESS with its management algorithm, power import from the grid decreases up to 49.3%.

1. Introduction

The recent advances obtained in the field of small-scale generation and electrical storage, involve changes in the way in which the generation and distribution of energy have been conceived in recent decades. Consequently, the expansion of distributed generation employing photovoltaic systems with storage leads to essential challenges in the planning, investment, operation and regulation of traditional electricity distribution systems [1,2]. However, for interconnected systems, this type of generation implies a change in vision. The end user will be able to manage the energy produced, delivering it to the low voltage system, during periods of maximum demand or valley, using the strategies of demand shift and demand reduction [3]. This vision would allow, among other things, to decrease transmission and distribution losses, increase system slack and reduce dependence on the centralised system. Consequently, it is convenient to identify the technical interconnection conditions for these new generation and storage systems, in such a way that the levels of reliability established within the electrical system are maintained.

One of the undeniable characteristics of the electrical energy generated by the photovoltaic systems is that it is not dispatchable due to the intermittency and unpredictability of the primary source of energy. This makes difficult to predict the power that will be generated by the system in a specific moment of time, as verified [4–6]. This uncertainty associated with the dispatch by the photovoltaic system does not generate significant inconveniences when it is only a user that is generating electrical energy from this source. However, when it is no longer a single user, but multiple users within the electrical system injecting power from non-manageable sources located at scattered points in the network, this uncertainty is significantly affected. The most discussed topics are related to the generated power fluctuations, voltage instability and frequency deviations, imbalances, among others [7–10,29]. However, this impact on the network can be mitigated by the integration of energy storage systems in optimal points of the electric network. However, it is necessary to evaluate the amount of energy that should be stored and integrated into the network [11,12], to mitigate these disturbances by performing the optimal dimensioning of the associated storage. For instance, Ref. [29] presents real applications of BESS, since 2011 to 2016, to balancing load peaks and valleys, frequency regulation, ramping, energy time shift, and voltage support among other by incorporating renewable generation.

Considering the high temporal intermittency associated with generation and limits on storage size the storage capacity is usually calculated only for short-term supply as work in [8,13]. Besides, the optimal size and location of energy storage can be considered as support to the operational planning of the system with the massive insertion of photovoltaic systems, to maintain the power quality and reliability of the electrical system [14,15]. Therefore, battery energy storage can be

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considered as a feasible solution to effectively get a reliable and safe power system based on PV generation. Then an analysis of the references found that address the problem of battery charging/discharging strategies that are integrated with PV is presented.

Thus, in Ref. [7] a control method in a DC topology for state-of-charge and battery charge/discharge is proposed to ensure efficient performance and safe operation of the storage system in combination with PV generation. The effects of the Active Demand-Side Management (ADSM) and storage systems for a single user in the amount of consumed local electrical energy is studied in Ref. [10] through a real installation of PV generation, lead-acid batteries, controllable appliances and smart metering. Moreover, in Ref. [14] a decentralised storage management strategy based on voltage sensitivity analysis, identifies a common power threshold that triggers the ESSs activation in the feeder to effectuate voltage support in low-voltage residential feeders with high PV capacity installed. In Ref. [17] a power management strategy is proposed for solving the cooperative operation of the energy storage systems and PV units in a multi-master micro-grid structure when local loads power demand changed. Additionally, an energy management strategy based on stochastic dynamic programming for a smart home with a plug-in electric vehicle as energy storage system and PV array is developed in Ref. [27]. Also, an optimisation framework based on convex programming for efficient energy management and components sizing of a smart home with battery energy storage, plug-in electric vehicles and PV arrays is presented in [28]. Furthermore, an active-power management scheme for the control of centralised battery energy-storage systems for large PV capacity firming and energy time shift is developed in Ref. [31]. On the other hand, Ref. [32] proposes an energy management system as a low-pass filtering algorithm with variable time constant which focuses on the power-sharing between the battery and supercapacitor due to PV power fluctuations with two optimisation objectives: energy loss and state-of-charge. Finally, in Ref. [33] is presented an energy management and control system for laboratory scale isolated microgrid based on hybrid energy resources such as wind, solar, and battery storage mainly to keep a constant DC-link voltage under various loads and supply conditions.

In most of the related literature, few articles deal with multiple BESS + PV in a decentralised manner. However, these works do not consider the simultaneous activations of the BESS to provide power losses reduction and voltage support. In this sense, this article presents a new control algorithm for battery energy storage systems (BESS), embedding as a battery management algorithm for charging and discharging process based on the PV power generation and load behaviour. This approach demonstrates through a typical network that the impact associated with the growth of photovoltaic generation is clearly mitigated with an intelligent control strategy for the storage. For this study, multiple simulation cases have been carried out on a CIGRE standard low voltage distribution network [9], where photovoltaic generation systems with battery storage (PV + BESS) have been incorporated in different nodes. The objective is to assess the impact that its operation will cause in the planning of low voltage networks, before a future massification of this type of systems.

In Section 2 the topology of the PV + BESS system and its grid-connected operating modes are described. In Section 3 an overview of the test grids, the definition of the mathematical models of the demand, the photovoltaic generator and the storage system, together with the intelligent management strategy are shown. In Section 4 the results obtained from five case studies evaluated on the selected distribution network are presented. In Section 5 the conclusions, summary of contributions and hints on future works are presented.

2. The configuration of the PV + BESS

Fig. 1 presents a topology based on the coupling at the AC side, in which the photovoltaic generation and storage system work independently. As a result, this configuration presents the complexity of synchronism in its operation and, besides, the photovoltaic system does not allow charging the storage system directly, which reduces the energy efficiency of the whole. However, this does not limit the advantage of adjusting the operating parameters of the storage set depending on the photovoltaic generation system, as demonstrated in [16,17]. In this way, the energy balance of the electrical system is managed by the aggregation of PV + BESS, according to the instantaneous energy demand.

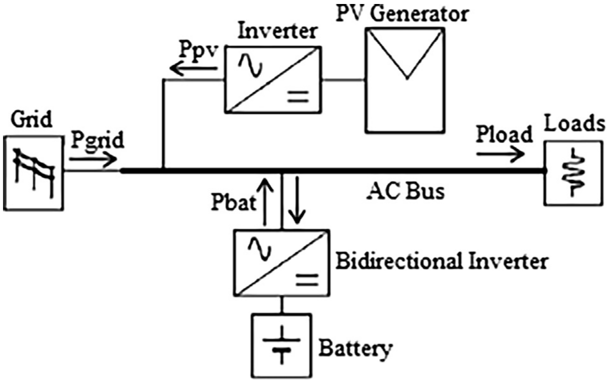

Fig. 1. Configuration of the PV + BESS.

From the customer's point of view, the best benefit is to minimise the cost of the energy consumed from the network. Based on this consideration, and the model presented in Fig. 1, if the user's daily load profile is known, it is possible to determine an optimal daily operation pattern from the network's point of view, as well as for the user. Consequently, the daily operation of the PV + BESS could be divided into four modes of operation, depending in the period of the day, as shown in Table 1.

Therefore, to avoid the PV energy spills during high irradiance periods, it has been established that the storage system can only be charged with the energy from the photovoltaic system, so that it can be used at night, minimising the contribution by of the network (Mode 3). Therefore, the instantaneous energy balance of the system is shown in (1):

$$E_{grid\,(t)} = E_{load\,(t)} - E_{PV\,(t)} - E_{bat\,(t)} \tag{1}$$

where $E_{grid\ (t)}$, represents the electrical energy imported from the grid; $E_{Load\ (t)}$, is the total demand; $E_{PV\ (t)}$, is the energy contributed by the photovoltaic generation, and $E_{bat\ (t)}$, is the stored energy in the storage system.

3. System modelling and energy management system

3.1. LV distribution system

A low voltage distribution network (LV) representative of a real European electrical system, proposed by CIGRE, was simulated with Simulink. The network comprises three load feeders: residential, industrial and commercial. However, the present study was developed on the residential branch of Fig. 2 where it has been installed the PV + BESS assemblies at the domestic level. The detailed information of the distribution system is shown in [9].

3.2. Demand characterization

The selected demand profile is based on average annual energy consumption of 3370 kWh/year [18], for a typical house in the Basque Country. The annual normalised profile applicable to consumers with an installed electrical power lower than 10 kW according to regulation [19] was taken as a reference, to determine the behaviour of the demand. Because load varies by a considerable amount throughout the

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