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Review of Residential PV-Storage Architectures

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***Abstract*— This paper focuses on the most common PV-storage architectures that are designed for residential applications and that incorporate storage devices like batteries, hydrogen systems, supercapacitors, and flywheels. The main motivations and a comparison of the advantages and disadvantages of the architectures are presented. Moreover, some common approaches to perform intelligent power management are introduced.**

I. INTRODUCTION

Solar photovoltaic (PV) energy enables the production of electrical energy either by centralized generation plants or by small-scale applications. Through distributed generation, it is possible to have bidirectional power flows in the distribution network. This has changed the roles of consumers and producers in the energy market. Nowadays, a typical consumer has the potential to feed power into the grid, resulting in a more clean energy generation.

The uncertainty and uncontrollability of the solar irradiation is a challenge for energy systems, leading to unreliability and instability in the electricity supply. This is due to the mismatch between the output power from the PV modules and the power needed from the loads. A way to cope with this, is by incorporating energy storage systems to supply power when there is no irradiation, or when it changes rapidly [1][2]. Therefore, benefits of integrating PV and storage systems could be obtained by PV system owners and utilities.

Previous studies have listed a wide-range of energy storage options [3][4]. At the moment, the authors have not found any study focused on the comparison of PV-storage set-ups for residential installations. In this paper, we review the different motivations and types of set-ups that integrate PV and electrical energy storage for residential applications. The advantages and disadvantages of the technologies are presented, also different approaches to achieve an intelligent power management in such systems will be discussed.

It should be noted, that energy storage systems like pumped hydro and compressed air were not taken into account in this study, since they are more suitable for large-scale installations. Superconducting magnetic energy storage is not included, due to its high implementation cost and low maturity of the technology [5].

II. MOTIVATION TO INTEGRATE PV MODULES AND ELECTRICAL ENERGY STORAGE

Some years ago, the applications of electrical energy storage was commonly related to off-grid solutions. However, nowadays, as more dynamic scenarios emerge, electric energy storage are implemented to: reduce the cost of the energy bill by allowing the user to react to differentiated tariffs, preventing the use of energy from the utility in instants of high electricity consumption, avoid overvoltage events to ensure power quality, provide less variation in the load, and stimulate the self-consumption. PV-storage systems implemented by using batteries, fuel cell-electrolyzer-tank systems, supercapacitors, and flywheels are the focus of this paper.

A. *Cost reduction*

The reduction of electricity bill and the maximization of profits are the most common motivations to incorporate storage as part of a PV system, from the perspective of the household owner. Countries like Germany, have defined economic incentives for the consumers to incorporate batteries in their PV systems [6]. Therefore, an optimal sizing technique is necessary to decrease the initial investment.

Depending on the location, the price of the electrical energy could change during the day (high consumption hours result in high retail prices), especially in the morning and night, when the residential consumption peak occurs. Some companies offer Time of Use programs, in which they charge with differentiated tariffs depending on defined time slots. For this reason, it is convenient to use the energy stored to increase the self-consumption [7] or feed the grid [8]. The key from the economic perspective, is to define which process is better under certain circumstances. For example, some economic energy management strategies can be performed in order to store energy when energy is cheap and sell it at higher prices during peak household consumption situations [9].

On the other hand, there are scenarios that have to be prevented as they result in an increase of the payback time of the PV. For instance, when the voltage regulation is not fulfilled, the inverter might be disconnected from the grid [10], causing an energy dump with economic consequences. It can be observed in [11], that even for the grid utilities, the integration of PV storage could result in cost savings, allowing new incentive programs to foster the installation of energy storage. Also, in [12] it has been proven that integrating a battery even without policy incentives, increases the profitability of the PV-storage systems.

B. *Peak shaving*

From the utilities' point of view, the consumption peaks can be shaved if the surplus of PV energy is stored and used during high consumption times, avoiding an increase of capacity, or the use of high cost generators [13]. The stored energy can be used to feed the residential loads or to sell it back to the grid. This decision is usually guided by the local regulations in which the PV systems was installed, to get the highest revenues.

C. *Prevention of overvoltage*

High penetration of solar energy can lead to overvoltages at the point of common coupling [14]. This overvoltage is associated with periods of high PV generation, resulting in loss of renewable energy (because of the disconnection from the grid) if the nominal peak power for instance reaches the 70% of the nominal peak output of the PV modules [15]. The European standard EN50160 specifies that 95% of the 10 minute average RMS voltage at medium and low voltage level must be within 10% of the nominal voltage [16]. Moreover, the impact of the R/X ratio was studied in relation to overvoltage events, and how energy storage can help to prevent it [17].

D. Self-consumption and rural installations

Arguments like, continuous rising of electricity price, black outs, financial crisis, cut down on subsidies, and feed-in-tariffs foster the idea that autonomy (off-grid) or at least less dependency on the utility grid. In places located far away from the electrical grid the use of energy is vital, hence PV-storage options becomes a vital alternative [18].

E. Others

Frequency regulation by injecting or absorbing reactive power at low time response times (1s) could be employed to stabilize the angular frequency. Long-period interruptions of power can be also addressed by incorporating a storage energy solution [19].

III. CHARACTERISTICS OF STORAGE TECHNOLOGIES

Electrical energy storage technologies can be described using a Ragone chart (Fig. 1) according to the ability to deliver power, time response or energy capacity. Based on that, supercapacitors can provide high response times (seconds) with high power output, but they have a low energy density [20]. Hydrogen storage systems are generally composed by an electrolyzer, tanks and a fuel cell; being able to store considerable amount of energy with low power ratings. Batteries in general, are characterized by their medium energy output and power density. In the case of the flywheel, high energy storage and high resultant power can be achieved. For residential applications the feasibility of the storage technologies or architectures can be evaluated according to: complexity of the architecture, load response, implementation cost, specific energy, specific power, cycle life, reliability, self-discharge and efficiency.

A. Battery based architectures

Batteries are a mature technology, and the prices are decreasing [21]. Moreover, new technologies of batteries have been introduced, increasing the round trip cycles, life time, replacing the toxic components and improving the safety. However, the prices are still high, the chemical elements used are not abundant, and the life time is considerably lower when it is compared with the PV modules. Another drawback, is the decreasing efficiency due to extreme temperatures, high C-rates, and profound depth of charge. In comparison to fuel cells systems, batteries operate at higher round-trip efficiencies with better incomes, in specific cases [22].

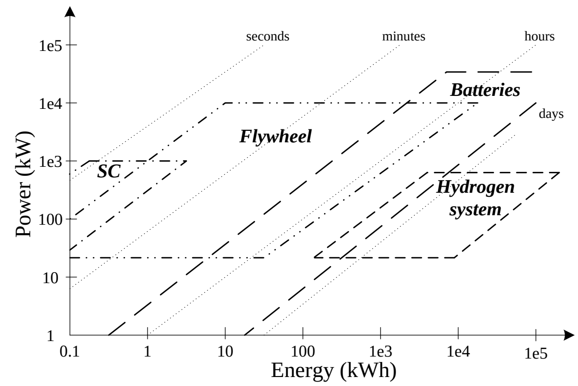

Fig 1. Ragone chart for different EES systems.

B. Fuel cell based architectures

Fuel cells are beneficial because of their capacity to serve as back-up power for long and short period interruptions, such as black outs. In addition, they can provide a back-up to loads in environments with drastic seasonal changes. Fuel cells as independent sources of energy are considered slow to respond to dynamic loads [23], however a recent study has shown their ability to perform load following [24]. For this reason, a battery or supercapacitor is frequently used to support a fuel cell. Moreover, fuel cells are space consuming and a low efficient solution when compared to batteries. The relatively high complexity of hydrogen systems ends in significant installation and maintenance costs. In [25], a comparison between fuel cells and batteries was done, with the conclusion that for similar efficiencies the fuel cell system cost is 1.5 times higher.

C. Flywheel based architectures

The ability to respond fast to the changes in the load demand side and the high cycling are the most valuable features of flywheels. On the other hand, disadvantages such as low energy storage, safety, high cost and self-discharge have been reported [3]. One of the reasons of the expensiveness of flywheels is related to the system's need to generate the appropriate vacuum conditions in order minimize friction losses.

D. Supercapacitor based architectures

A supercapacitor is often utilized in hybrid storage systems to perform as a power source in case of load following techniques. The supercapacitor is considered as a support device in a PV-battery systems. The cycle life is considered its bigger advantage. As a result, many research efforts have been made to elevate the energy density [1].

E. Fuel cells and supercapacitor based architectures

Systems that combine supercapacitors with fuel cells do not show advantages from neither, performance nor cost. The main reason is the very low energy density of supercapacitors. As a result, the supercapacitors are depleted of energy before they can meet significant power demand and, when connected to the grid,the grid is needed to support the system [26].

IV. PV-STORAGE ARCHITECTURES

In this section the general architectures to implement PV-storage architectures are presented.

A. *PV-battery architectures*

1) In line systems

In this simple architecture, the battery is connected to the PV modules using a unidirectional converter (Fig. 2). Its function is to perform maximum power point tracker (MPPT) and to supply energy to the battery or the inverter. The inverter could be bidirectional to make the system more flexible in terms of power flow. The size of the converter and inverter is subject to the PV modules rated power (voltage and current), restricting the system. To control the power flow, a communication between the converter and inverter is necessary.

2) DC coupled systems

A common dc bus is used in order to allow the PV and the battery to work in parallel (Fig. 3). The battery can either get energy from the grid or from the PV modules, giving more flexibility in terms of power management. In order to do that, the converter tied to the battery must be bidirectional (charge controller). The converter that is directly connected to the PV module can perform MPPT, being limited to the size of the PV module. The battery size and charge controller are sized independently. A drawback is that the inverter must be highly robust, because all the power flows through it, and therefore is considered a single point of failure [28]; this is also applicable for in line and dc/ac coupled architecture. Another characteristic is the ability of the energy storage to feed the grid or the loads of the households. This architecture can operate in various modes as shown in [8]. By using a dc bus, it can act as a link to build a dc microgrid with the specific benefits over ac systems [29]. This architecture, can be used for charging electric vehicle batteries, as both are of dc nature [30].

3) AC coupled systems

In the ac coupled system (Fig. 4) both the PV and battery are completely independent, in this case with the absence of a common inverter. This gives the option to size every part of the systems independently, without the limitations of one over the others. As a result, the modularity of the system is achieved. A connection to the grid and local load [7] might provide more flexibility to the system in terms of charge and discharge of the battery and the peak time management.

4) DC/AC coupled systems

An architecture with residential dc bus and residential ac bus is presented (Fig. 5). In this case, the PV modules and the battery have a connection through dc/dc conversion processes with the dc bus. The ac bus is interconnected via a dc/ac inversion process with the dc bus. The residential level ac loads are fed by the ac bus whereas the dc loads via dc bus. The architecture shown in Fig. 5 is similar to the dc coupled architecture. The benefit of this architecture is that it allows to allocate the loads based on their nature (dc or ac). However, this results in a more complex control algorithm. Due to the fact that many of the household appliances work in dc, as well as the generation sources (PV and battery), in order increase the efficiency of the system, the dc/ac coupled set-up is convenient. The efficiency is higher, as it avoids the unnecessary conversion steps between ac and dc. In more conventional architectures, where all generation devices and loads are connected to an ac bus, there is always an extra transformation step in order to deliver power to dc devices. This occurs even when the power comes directly from a dc generation device, like PV or from a battery [31]. It provides high level of flexibility as in off-grid rural applications where both dc and ac loads can be independently connected [32]

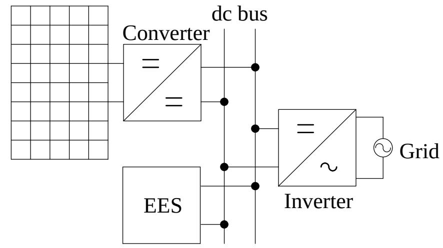

Fig 2. In line architecture.

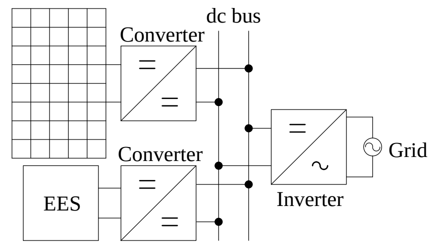

Fig 3. DC coupled architecture.

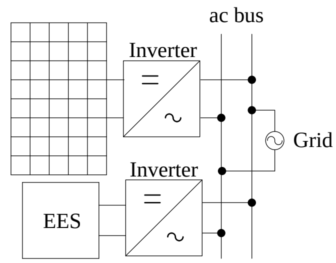

Fig 4. AC coupled architecture.

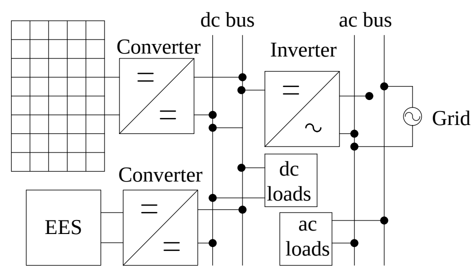

Fig 5. DC/AC coupled architecture.

5) Others systems

The last PV battery architecture considered in this paper is reported in [33], in which two battery banks have been proposed, each of them with different goals. One provides a primary buffer and the other battery is managed to balance the existent difference between the expected irradiance and the user load forecast.

B. PV-battery/fuel cell

In this case, the hydrogen system is used as an auxiliary source, it can act both as a power source, but also as a battery charger [34]. Normally the battery, electrolyzer, and fuel cell are connected by a dc bus, using an appropriate converter. In comparison with the ordinary PV battery diesel hybrid systems, the drawback is the slow response time of the fuel cell to reach a rated power, because of the temperature of the process. In [35], the hydrogen system was planned as a back-up generator.

C. PV battery/supercapacitor

The equivalent circuit of integration of PV module battery and the supercapacitor is reported in [20]. The battery and supercapacitor fulfil the task to keep the dc bus (dc coupled) output voltage fixed and to perform real time load following, the extra power available on the dc bus is stored in the supercapacitor, and released when the power from the sources is reduced [27].

D. PV-fuel cell

In the case of PV-fuel cell set-ups, the production of H_2 by the electrolyzer is done during the off-peak electricity demand, and stored for high demand instants [36]. The oxygen for the chemical reaction could be taken from the air, and the tanks store H_2, to be used when it is required. In [35], the dc coupling, dc indirect coupling (no MPPT), and ac coupling is shown. For dc coupled architectures, the PV modules supply the dc bus voltage. Therefore, the maximum power point voltage should be the same as that of the maximum voltage of the fuel cell component and the electrolyzer. The dc/ac coupled system is proposed in [37], the benefits related to connecting the dc loads to the dc bus directly, and the ac load to the ac bus directly also hold in this case. This is done in order to avoid unnecessary conversion steps and is also applicable for the PV- fuel cell architecture.

E. PV-fuel cell/supercapacitor

The power response of the fuel cells is slow compared with the time changing load. To solve this lack of correspondence, one proposed solution [38] is to add a supercapacitor. Due to the supercapacitor's high specific power, it is able to reduce the incompatibility with the load and the fluctuation of the PV module output. In terms of energy, the system is balanced using the supercapacitor as a dc bus regulator. The main goal of the fuel cell is to maintain the supercapacitor charged all the time. The PV and fuel cells are used as an energy source and the supercapacitor as a power source [39].

F. PV- fuel cell/supercapacitor/battery

The hybridization solution in storage has been proposed to overcome the individual limitation of every technology. This normally results in more complex architectures. The PV and fuel cell configuration delivers power to the load and charges the battery; if the battery is completely charged the remaining power is sent to the grid. At no illumination conditions, the battery starts to discharge. In case this is not enough, the fuel cell helps to satisfy the load demand. An energy back-up could be added in case the hydrogen tank level is low. The role of the supercapacitor is to help the fuel cell to provide a dynamic power response to the load. Different scenarios for this architecture can be seen in [40].

G. PV flywheel

The architecture proposed in [41], is similar to Fig. 3. The flywheel stores energy (rotational energy) from the PV or grid and releases it to feed the load and balance the dc bus by using the dc/dc converter (bidirectional). It acts as a motor of generator according to the power requirements, the flywheel is driven by an induction machine, and in some cases a supercapacitor is added in order to control the power variation and the voltage levels [42].

V. INTELLIGENT POWER MANAGEMENT

Even though the architecture of the PV storage systems has its owns advantages and disadvantages, the way of managing the power flow plays an important role. Even if two set-ups share the same architecture, they can operate completely different depending on the power flow algorithm. An intelligent power management system consists of one or several of the following parts: forecast, optimization, and control. The control can be done at a centralized or at a decentralized level. The power management strategies that were identified in the literature contained one or several of these steps. Demand side management has also been considered in the analysis.

A. Forecast

To estimate the power that needs to be exchanged in the case of grid-connected systems, forecast methods become necessary. Many methods have been presented to predict the amount of energy produced by the changing illumination conditions, either for short (days, hours) [43] or long forecast periods (weeks) [44]. Load forecast is implemented in the literature [45] in order to provide information about consumption pattern. The outcome of both forecast is usually taken as an input in the following sections.

B. Optimization techniques

An optimization performed for the day ahead was presented in [46] using forecast and a quadratic program based minimization. Multiple optimization techniques [47] have been reported, for instance: multi-stage stochastic optimization [48], Lyapunov approach [49], particle swarm based, and fuzzy logic [50]. Additionally, to optimize the cyclic operation of battery, genetic algorithms have been presented in [51]. Another example is the use of a mixed integer programing optimization [52] to minimize the running cost of the system. The optimization time must be reduced as much as possible, to be capable of working at real-time.

C. Control algorithms

Control algorithms are implemented to fulfil economical purposes [53] or to prevent overvoltages. Some control methodologies like adaptive control [54], fuzzy logic control [55] have been presented. Normally, the battery is charged when the power generated surpasses the power needed by the load, however a new strategy is proposed to charge the battery when a defined power threshold is reached [15]. Information as temperature and charge-discharge power are inputs to determine the state of charge and state of health of the batteries [56], which will determine energy interchange during the day. In [57] the main goal was to keep a constant power output to improve the quality of energy output. Control strategies for fuel cells were shown in [58], also control strategies for set-ups that include a supercapacitor and a battery [20]. In [59], the operation and control methods are reported for a flywheel architecture.

D. Demand side management

It is defined as a technique to change the energy consumption pattern, in order to obtain better efficiencies or savings [18]. In the case of renewable energy, it is performed to get as much energy as possible [7]. One of the limitations of this technique is that it does not work well if the number of flexible appliances is low [15]. By the use of load shedding strategies, the battery lifetime increases [60].

VI. CONCLUSION

A relative broad range of set-ups and electrical energy storage technologies are available for residential scale. As a result, the motivations and specific scenarios will determine the best selection. PV-battery is the most common solution in comparison to hydrogen systems and flywheels, specially to for cost reduction and peak shaving purposes. An intelligent power flow management is used to improve the performance of the systems. Forecast, either for load demand or PV production is vital, being usually incorporated as a input in the demand side management, optimization techniques, and control algorithms.

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