Hybrid Energy Storage Systems for Renewable Energy Sources Integration in Microgrids: A Review

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***Abstract*-The increasing use of the Renewable Energy Sources (RES) and the intermittency of the power generated by them create stability, reliability and power quality problems in the main electrical grid. The microgrid is called to be a feasible alternative to solve these issues. As it is a weak electrical grid, the microgrid is very sensitive to load or generation changes. To reduce the effect of these variations and to better harness the energy generated by RES, the Energy Storage Systems (ESS) are used. As the different ESS technologies that are currently available are not enough to satisfy the wide frequency spectrum of the generated energy, the use of a Hybrid Energy Storage System (HESS) is necessary.**

A HESS is usually formed by two complementary storage devices that can be associated in many different topologies. Of course, the two devices have to be coordinated by an Energy Management System (EMS). In this paper the different topologies and energy management algorithms that have been applied in the RES and microgrid contexts have been analysed and compared. A review of the latest papers related to the use of HESS to facilitate the integration of the RES in the microgrid context is carried out. Some examples of the (hybrid) electric vehicles are also addressed, as the use of the HESS is more extended in this field than in the field of the microgrids.

Keywords: energy management, energy storage, microgrid, power converters, renewable energy.

I. INTRODUCTION

The global climate change and the current contaminating generation systems have promoted the use of Renewable Energy Sources (RES), being the most used the wind turbines [1] and the photovoltaic panels [2]. The problem of those generation systems is that their energy sources (wind, sun) are intermittent and so the generated power is intermittent too. This fact generates stability, reliability and power quality problems in the main electric grid. The microgrid is being analysed as a feasible solution for these problems

A microgrid is a weak grid formed by microsources, storage systems, power converters and loads. The microgrid can operate both connected to the main grid and in islanding mode. This system is used to overcome the intermittency and uncertainty of the RES, in order to create a "good citizen" load/generation system from the main electric grid point of view [3]. In this context, the use of the ESS is a widely accepted idea, as they can smooth the variability of the generated power, avoid power quality problems, and control the frequency and the voltage of the microgrid.

Due to the sensitivity of the microgrid to load/generation changes, it should have a storage system with both high energy and power densities. However, none of the currently available ESS technologies satisfies these two features. For that reason, it is necessary to combine two or more ESSs [4] creating a Hybrid Energy Storage System (HESS). The HESS is usually formed by two complementary storage devices, one of high energy density and the other of high power density. The use of a unique ESS, usually of high energy density but low power density, creates power control problems as the response of these types of ESS is slow. Furthermore, a high power demand usually affects negatively the lifecycle of the storage system, reducing it. Adding a short-storage system the operating conditions of the main storage system are alleviated, prolonging its lifecycle and simultaneously permitting to satisfy the power requirements. In addition, the use of a short storage system in parallel to a long-storage one reduces the size and the power losses of the main storage system as it has been proved in [5]. In this paper, the behaviour of a system when it has a unique ESS (Vanadium Redox Battery, VRB) and when it has a HESS formed by a VRB and a SuperCapacitor (SC) is compared. The results show that for the same wind-power profile the maximum power for the VRB in the HESS is less than the half of that in the unique ESS. The VRB depth of discharge is 5-8% less in the HESS and the power losses referred to the storage are also reduced in 15%. In [6] similar results are obtained. The size of a reversible fuel cell and a battery are reduced in 75% and 64% respectively when they are associated creating a HESS, than when they were used as unique ESSs.

The power converters are used as interfaces between the ESS and the microgrid, to control the power flow of the storage devices (bidirectionally) and operate the system optimally. However, the power losses of the converters (mainly switching losses) and their economical cost are limiting factors for their use. Although there are methods like the soft-switching [7], [8] designed to reduce the switching losses of the PCS, depending on the application, in some cases it is more economical not to use it. A trade-off between the technical advantages and economical disadvantages must be done. Hence, there are different topologies and architectures of the HESS that can be used for the same application.

Another aspect related to the HESS is that it creates new issues related to the energy management: the power division among the different storage devices and their coordination to satisfy a shared requirement, a better integration of the RES and the maintenance of the power balance of the system. The energy management of the HESS affects the size of the storage systems, their lifecycle and their efficiency among other characteristics. The selection of a proper energy management algorithm is, therefore, crucial to properly size the HESS and to obtain an optimized utilization of the whole system.

In this paper a review of the latest papers related to the use of HESS to facilitate the penetration of RES in the microgrid context is carried out. The use of the HESS in other type of applications is also taken into account in order to analyse all the used solutions. HESS formed by different storage systems and with different topologies are analysed and compared.

The paper is divided as follows: in the section II the different topologies of the HESS are analysed; in section III, the control strategies used in different research works are exposed; in section IV, a comparison among the different topologies and control strategies is carried out; in the section V the conclusions are presented.

II. HESS TOPOLOGIES

ESSs have been used in multiple applications connected with power converters in many different topologies. The advantages of the ESS are well known and they are widely accepted. However, the idea of associating two ESSs in a microgrid has been addressed just in few research works.

In a HESS the different storage devices are connected to a common bus, which can be of DC or AC type. However, in almost all applications the selected common bus type is the DC. This is because most of the storage devices are of DC type (in flywheels the high frequency AC voltage has to be transformed to DC), and so a DC common bus facilitates their implementation. Furthermore, in a DC bus no synchronization is needed, as it is in the AC bus [9]. Finally, as it has been proven in [10], the DC bus is more efficient and less costly than the AC bus.

Analysing the papers that use a HESS [5], [6], [10]-[28] the following classification of the topologies has been concluded:

- Series
- Parallel
  - Direct connection of the 2 devices (passive topology)
  - Connection via power converter (active topology)
    - 1 Power converter (for long/short term storage device)
    - 2 power converters (one for each storage device)

The ESSs can be connected in series or in parallel, but leaving aside a few exceptions related to concrete applications (for example [11]), they use the parallel architecture. In the given example, the series connection (see Figure 1a) allows a simplification in the architecture of the system and reduces the cost of the short-term storage device (a SC). This is because it does not need a high voltage in the DC bus and, therefore, just few SC cells can be used. However, the power distribution of the system is limited because it cannot be divided between the two ESSs: the regenerated power is completely absorbed by the SC and the battery cannot be charged using it. The series connection reduces the flexibility and the power capacity of the system. Because of that it is not well suited for microgrid and RES application.

In [12] and [13] the two ESSs are connected directly in

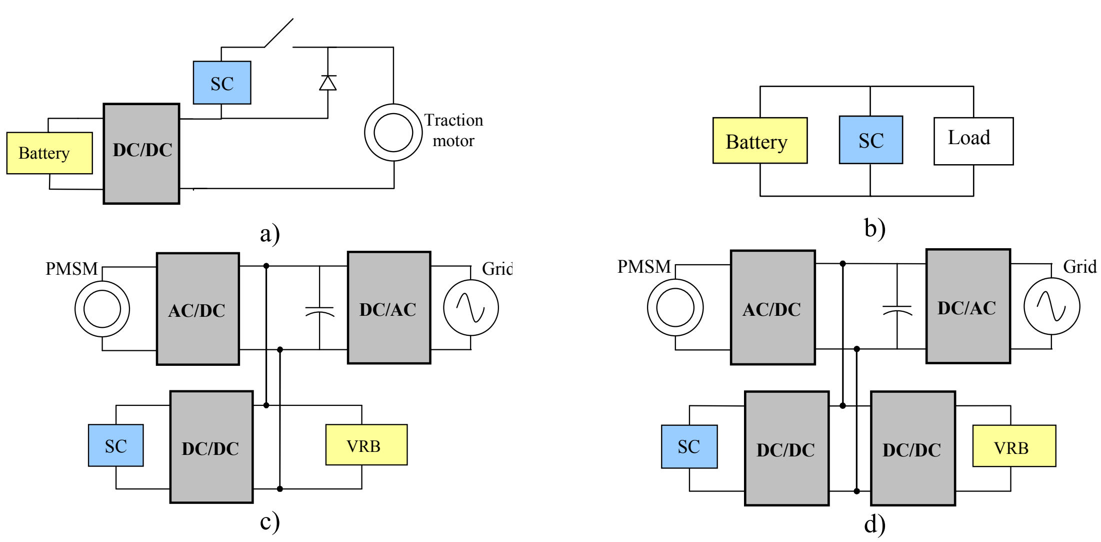

Figure 1. a) Series topology [10]; b) Parallel passive topology [14]; c) Parallel active topology (direct connection of an ESS to the DC bus) [4]; d) Parallel active topology (both ESS with a PCS) [4].

parallel (a battery and a SC bank), using a passive configuration (see Figure 1b). Although some of the benefits of a HESS are also obtained in such a simple topology, the storage system capabilities are not completely harnessed. The current is divided between the two devices depending on the internal resistances, and so the power flow of the system cannot be controlled. On the other hand, the voltage is the same for the battery, SC and the load. This limits the SC from being exploited optimally because its voltage is fixed by the battery. The voltage of the battery also limits the selection of the array size of the SC bank, because they must have the same voltage. Furthermore, this voltage cannot be controlled and it varies according to the State-Of-Charge (SOC) of the battery. Using a power converter as an interface for the SC permits to actively control its power flow, and so an energy management algorithm can be designed and applied. The SOC of the SC can be controlled and it can be charged or discharged until the selected value. This topology is called active topology (see Figure 1c or d).

A comparison between the passive and active topologies is carried out in [14], [15] and [16]. In the first case, the two configurations are compared by means of simulations: the results show that using the power converter the battery peak current is reduced in 40%, the DC bus voltage control is improved in 30% and the SC characteristics are better harnessed. In the second case, simulation and experimental results show that the power density of the active HESS is 3.2 times higher than the passive one and that the battery current is drastically decreased, obtaining a much more stable DC bus voltage. Another important conclusion is that the 50% of the power losses of the active HESS are related to the Power Conversion System (PCS), stressing the importance of an efficient switching strategy for the converters. The paper [16] shows that using a PCS the same run-time improvement as in the direct connection of battery-SC can be achieved, but with the half quantity of SC cells.

Hence, the parallel connection of the ESS needs a PCS to directly control the power flow of at least one storage device and to optimize the system. In the literature different topologies can be found depending on the requirements of the application. In some cases the direct control of the ESS is necessary because its SOC has to be controlled; in other cases the application is not so demanding and the long-term storage can be directly coupled with the DC bus.

In almost all applications, the short-term storage is connected using a PCS to the DC bus. However, in [15] the PCS is used to control the power flow of the long-term storage, while the short-term storage is directly connected to the DC bus. This topology is able to reduce the current demand for the battery and so to prolong its lifecycle. Its main drawback is that the SC has a low voltage, and so it is necessary to connect many SC cells in series to obtain a high DC bus voltage. In addition to that, during the on interval of the pulsed load current, the SC voltage and consequently the load voltage experiments a decrease of 27%. This decrease can create problems if the load needs a constant voltage or if the DC bus voltage is connected to an inverter (as it needs a minimum voltage to work properly [5]).

A more logical topology of the same system consists of connecting the long-term storage to the DC bus and to control the power flow of the short-term device using a PCS (see Figure 1c). This is the topology used in [5]: a HESS formed by a VRB as long-term storage and a SC as short-term storage is presented for wind-power smoothing application. The voltage of the DC bus will vary according to the SOC of the VRB, which has to be maintained inside a given range because the voltage cannot go down from the value needed by the inverter. This type of topology has the advantage of suppressing a PCS for the VRB, and so its power losses will be also eliminated, which is a key parameter in ESSs. The trade-off is that the operation of the system is limited because the bus voltage must satisfy an operation range and it depends on the SOC of the VRB, variable that cannot be directly controlled.

The same topology but with different ESS is presented in [17]: the HESS is formed by a battery and a Superconducting Magnetic Energy Storage (SMES) device, and is used to smooth the power generated by a wind turbine and to supply a varying load, a railway. It is shown that a unique PCS (used as interface for the SMES) together with an adequate EMS is able to maintain the SOC of both storage devices inside the given ranges. However, the voltage of the DC bus varies according to the SOC of the battery, which can be a problem for the correct operation of the inverter. Of course, this depends on the application: on the load requirements, the ratings of the storage devices and the generation system. In some cases the DC bus voltage variations can be accepted if they do not go under a certain value taking into account the worst case of the system.

The papers [18] and [19] present a HESS for the same application, where both storage devices have a DC/DC converter as interface. In [18] the storage device types are not specified (medium-term and short-term storage devices), whereas in [19] the HESS is formed by a VRB and a SC bank (see Figure 1d). The use of a PCS for each ESS permits to control both storage devices directly and at the same time to maintain constant the voltage of the DC bus. The battery can be discharged more deeply and so its energy capacity will be better harnessed. In general, the use of a PCS permits to directly control the SOC of the connected ESS and hence the storage device can be used optimally, which permits to optimally size the ratings of the storage devices. The use of a PCS gives more flexibility to the EMS.

In the (hybrid) electric vehicles application the most used HESS is formed by a battery and a SC bank. In almost all the cases the used topology consists on a PCS connecting the SC to the DC bus, where the battery is directly connected [20]-[24]. As such, a PCS is avoided, which is beneficial from the power losses point of view as well as from the physical space point of view. However, in [25] and [26] both the long-term and the short-term storage devices are connected via PCS, proving the feasibility of this topology in the electric vehicle application.

III. Energy Management Strategies

The parallel connection of more than one ESS creates coordination and power distribution problems [18] among other issues. The energy management system (EMS) plays a vital role in order to minimize both the size and the ratings of the different ESS and PCS, and to obtain an optimal system operation. It is the responsible of creating power references for the low order controllers of the PCS (see Figure 2). In [6] the effect of an EMS on the behaviour of the system is shown. Two different EMS are applied to a same hybrid system formed by photovoltaic generation panels, a reversible fuel cell, and a battery. It is shown that when the EMS tends to use the battery, the fuel cell is rarely used, and in the case that is used it is not enough to satisfy the power requirements; thus, the main grid has to be used. When the EMS tends to use the reversible fuel cell, the system efficiency and the hydrogen generation are improved and the power requirements are satisfied without using the grid.

One of the used methods to distribute the power among the storage devices is the linear filtering. The power references can be created using linear filters, distributing the power among the storage devices depending on their response times: the low-frequency power part is assigned to the long-term storage device, and the rest is absorbed/supplied by the short-term storage. This simple algorithm has been applied in [5] and [19] in order to carry out some simulations. However, this power distribution method is not enough to coordinate the HESS. The power losses of the storage devices, their response times and state of charges, the power-energy limitations and in some cases predictions of the power generated by the RES are some of the concepts that have to be taken into account by the EMS.

Although the linear filtering is not sufficient to optimally distribute the power, it can be used as a first power distribution algorithm. These references will then be adjusted using more complex algorithms depending on multiple variables and factors: some examples of these algorithms are the rule-based, fuzzy and neural network-based algorithms (see Figure 2).

In [17] the power reference given by the linear filter is modified using a fuzzy algorithm. This algorithm divides the power references depending on the SOC of both ESSs in order to avoid the saturation or the depletion of them. The SOC of the SMES and the battery are maintained between 33-100% and 50-100% respectively. In [18] a control algorithm based on neural networks is applied to a HESS formed by a short-term and a medium-term storage device. The power references generated by linear filters are modified by a knowledge-based algorithm, which uses neural networks, when the reference is 0 or when it is near to the upper/lower limit of the ESS. The advantage of the knowledge-based algorithm is that it takes into account the SOC of both ESS, and it is able to rebalance the power depending on their value. The operation of the proposed system has been proved in two situations: in a constrained connection of the wind-generation with the main grid, and in the islanding case. In the latter case a reduction of the 20% of the storage rating has been obtained comparing with the rating obtained with the linear algorithm.

In [27] a HESS formed by a Compressed Air Energy Storage (CAES) device and a SC bank is presented. Each of the storage devices is connected to the DC bus via PCS. In this case the control algorithm of the power distribution of the system is different comparing with the other presented algorithms. Taking into account the low efficiency of the CAES, the main objective of the used algorithm is to work on the maximum efficiency point of that storage device. Because of that, the used algorithm is known as maximum efficiency point tracking (MEPT). The PCS of the SC bank is controlled in order to maintain constant the DC bus voltage. The proposed control algorithm permits to improve the energy conversion efficiency of the CAES.

The HESS are also being used in (Hybrid) Electric Vehicles (HEV, EV), and thus the energy management problem is also addressed in this field. In [22] the power reference given by the linear filter is modified using a corrective algorithm based on a heuristic algorithm. As such, the voltage of the SC bank is controlled using a DC/DC converter while the battery transitions are smoothed. In [20] a rule-based algorithm is used to generate the current references for the unique PCS of the system. The objective of the algorithm is to maintain the SOC of the SC at a given level depending on the speed of the vehicle. The obtained results show that the algorithm reduces in 36% and 25% the supplied and absorbed current peaks. Furthermore, the current density is reduced in consideration.

The same topology is used in [21]. Two different EMS are applied to the HESS and compared with each other. The first one is a heuristic method based on two rules, the regulation of the SOC of the SC bank and the control of the current of the battery to maintain it inside a certain range. The second one is an optimized method based on a neural network. The experimental results that are given are related to the electrical

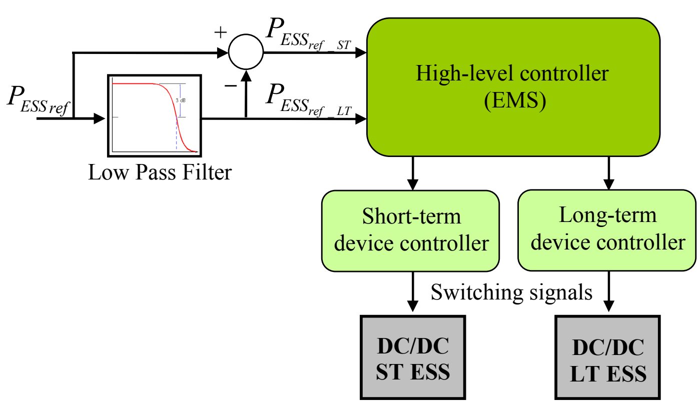

Figure 2. Example of a power reference creation using the linear filtering.

consumption of the applied methods, when the vehicle covers the same route. The efficiency measured in Km/KWh has been improved in 6.2% with the heuristic method and in 10.5% with the neural network, in comparison with the HEV that has just the battery. In parallel, the used KWh and Ah quantities have been reduced in 5.5% and 6% using the heuristic control, and in 8% and 5.8% with the neural network. Furthermore, the battery current is maintained inside the specified range as well as its depth of discharge, which prolongs the lifecycle of the battery. However, in the work there is not presented any information related to the use of the storage devices in order to compare the applied EMSs.

IV. Comparison, Analysis, Discussion

Although there are many technical and economical differences among the different topologies, there is not any unique solution for all the applications of the HESS. In fact, to select the best topology for each application an analysis of the different choices must be done to determine the advantages and disadvantages of each one, both from economical and technical point of view.

It can be seen that in almost all the papers that have been analysed in this work [17]-[25], [27] the selection of the used topology is not justified. However, in some of them the reasons of using a topology instead of another are given. For example, in [26] the selection of the topology that uses a power converter for each storage device is justified saying that it is the most sufficient configuration when comparing mass, volume and cost of the propulsion system of the electric vehicle. In [28] the same topology is selected for the same application. In this case the selection is based on the low DC voltage of the storage devices and the fuel cell: as the DC bus voltage is higher than these values, a DC/DC converter is used in each case. In the microgrid application, the paper [5] assures that the results obtained with the floating topology and using two power converters are very similar in a HESS formed by a SC bank and a battery for wind power smoothing application. This analysis is made by means of simulation and just the numerical results of the floating topology are shown. The same authors carried out a real time simulation for the topology that uses two power converters [19], a more detailed simulation taking into account the switches effect. The system parameters and the used models of the ESS are the same as in [5], but not the wind profile. In the latter case the wind profile is more demanding, but however, the system is able to satisfy the requirements and to work properly. As two power converters are used, the DC bus voltage is maintained constant, with little changes in the fast power variations. In these two papers the authors have proved the validity of both topologies for the microgrid application, but it is not possible to make a comparison between them because of the differences in the wind profiles.

The topology that is better suited for the integration of the RES in the microgrid context is, at first sight, the one which uses a power converter for each storage device. Using two power converters permits to directly control the power flow of each ESS, giving more flexibility to the energy management system. Another important result of using this topology, as it has been stressed before, is that the DC bus voltage will not vary according to the state of charge of the floating ESS. This permits to discharge more deeply the ESS without affecting the DC bus voltage. However, using a power converter introduces power losses and increases the economical cost of the system [15]. So, a trade-off between the technical advantages of using a power converter and the economical cost increase of the system must be done.

The DC bus voltage is directly affected by the selected topology: it must satisfy a given voltage range because it is connected to an inverter that needs a certain voltage level to properly generate the AC side voltage [5], [26]. Depending on the requirements of the application, the DC bus voltage variations will not be high enough to justify the use of a power converter, and the floating topology (i.e., the direct connection of an ESS to the DC bus) will be the best one; this is the case of the paper [5], where it is assured that the results of the two topologies are very similar, so to avoid a power converter would be the best option for this specific application and wind profile.

In the floating configuration of an ESS the voltage is limited by the ESS, it depends on its state of charge; consequently, for the same discharge power the discharge time of that ESS is smaller in the floating topology than in the other. So, to obtain the same discharge time the floating topology needs an ESS with a higher energy capacity. Furthermore, taking into account that usually the voltage of the different types of the ESS (all types of batteries, supercapacitors, etc) is not high, in almost all cases it is necessary to connect many modules in series to generate a proper voltage. As the batteries cannot have exactly the same features, the voltage distribution among the different modules connected in series is not equalized; this is because of differences on internal resistance, imbalanced state of charge between cells and degradation, among other reasons. Imbalanced voltages will cause overcharge or overdischarge of the batteries, diminishing their storage capacity and their lifecycle [29]. Thus, the series connection needs a strategy to assure the equalization of the voltages of the connected batteries, which increments the system complexity. This problem is not addressed in any of the analysed papers where the floating topology is used and many ESS modules are connected in series [21], [23]-[25].

The charge and discharge process of the ESS have also to be respected. In some cases (for example in batteries [28]), the ESS life time depends on its usage, and an aggressive use reduces it in consideration. Thus, this is another feature to take into account when selecting the topology.

Hence, the selection of the topology depends on different factors which have to be analysed in order to be able to choose the best option. However, this complete analysis is not analysed in any of the mentioned papers.

In the case of the energy management strategies that have been shown in this paper it is very difficult to make a comparison among them as they have been designed for different applications. The comparison would be only valid if the different EMS where applied in the same system (as in [21], see section III). The design of the EMS is directly dependant on the application and so it can vary in consideration from one application to another. However, it can be said that the advanced control methods as fuzzy and neural networks obtain better results than other simpler methods [18], [21].

V. Conclusions

In this paper a review of the latest papers related to the use of the HESS for facilitating the penetration of the RES in the microgrid context have been carried out. The application of the HESS in the microgrid context is not very extended, and so just few examples can be found. In the hybrid/electrical vehicles field the HESS have been used more widely, and because of that some examples of this field have been analysed; although the two applications are very different and the systems have different dynamics, the research done in the electric vehicles field can be helpful for the microgrid application.

The different topologies that have been proposed and applied have been analysed and compared. The most important factors that have to be taken into account when selecting the proper topology for the microgrid application have been shown. Using these features the different topologies have been compared. As each application has its own characteristics, different requirements, generation/load profiles, etc. it is not possible to generalise the solutions. An analysis has to be carried out in each case to define which the proper topology is. The different energy management strategies for coordinating the two storage devices that have been used in different literature works have been presented too.

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