Challenges for the Goal of 100% Renewable Energy Sources to Fit the Green Transition

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***Abstract*—The increasing penetration of Renewable Energy (RE) into the electrical market is desirable in terms of sustainability. Nevertheless, it is a challenge that all the interested actors shall address from both the technical and economical points of view. This paper provides an overview of the main challenges and solutions towards the technological transition to an electrical system with 100% renewable energy sources in terms of innovations and operative limits of the traditional systems. These innovative paradigms will also address the social impact and government policies.**

Keywords—Renewable Sources, Green Transition, Smart Inverters Introduction

I. INTRODUCTION

The sustainability of our planet is strictly related to a significant and constant reduction of environmental pollution in the next years. In 2015 the Paris Agreement was presented with the ambition of maintaining below 2°C the average temperature increase [1]. From this perspective, the technological transition of power production from traditional energy sources to 100% renewable energy sources represents a valuable and promising solution to the global climate change challenge, decreasing Greenhouse Gas (GHG) emissions. Indeed, this is one of the most relevant actual topics of all governments policy and it has gained considerable attention in the scientific community, as the National Energy and Climate Plans (NECPs) set out how the Member States will contribute to the EU-wide climate and energy targets from 2021 to 2030. Full implementation of these plans would put Europe on track to surpass its current 2030 targets for Greenhouse Gas (GHG) emissions reduction and Renewable Energy Sources (RES) shares [2]. For 2030, the current emission reduction target is set to 40%, whereas the expected reduction under existing targets would be 45%. According to the new directives, the proposed new 2030 emissions reduction target is raised up to 55% [3].

Furthermore, a climate-neutral energy system will need to rely largely on renewable sources. The share of RE by the 27 Member States should surpass the current target by 2030, but according to the higher targets of the 2030 Climate Target Plan (55% GHG emissions reduction), this progress should be accelerated further. For 2030, the current renewable energy target is 32%, whereas with planned and existing measures it can surpass 33%. Nevertheless, in order to achieve the 55% greenhouse gas emissions reduction, a 40% RES share is needed. A further increase in renewable energies penetration is therefore required, aiming at an ideal 100% both in EU and globally speaking.

The 100% Renewable Energy (RE) topic is a rather recent research field, as reported in [4]. Focusing on the only electricity sector, several countries already meet or come close to achieving the goal of a 100% Renewable Grid, also due to a large fraction based on hydropower sources, whose best sites have already been developed. For this reason, the "variable" renewable energy has to be improved, with a major contribution provided by both wind and solar systems.

As well known, electrical power systems are changing from centralized generation systems to distributed generation systems due to the increase in renewable energy sources. Shortly, the main grid will be composed of interconnected microgrids that can be managed and controlled independently. In particular, in a power system with conventional power plants, where synchronous machines are adopted, and distributed generation plants, where static conversion systems are used, the system stability is entrusted only to the conventional power generation system thanks to their rotating inertia and damping. Indeed, static power converters cannot provide inertia and damping to power systems, so they are vulnerable to power dynamics and system faults. Thus, power system stability is degraded as the penetration of renewable energy sources increases and this issue is amplified in a

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possible future power system with only renewable sources. In this perspective, the “Smart Inverters” concept represents a promising solution to overcome the operative limits of traditional renewable energy sources [5]. A Smart Inverter is a power converter capable of providing a proactive and autonomous decision based on local measurements and external data. This new concept allows obtaining an energy source able to perform different functions, in real-time operations, like grid-supporting mode to provide ancillary services or grid-forming mode in the case of islanded microgrid following a fault. In addition, innovative energy storage systems and hybrid solutions play an important role to ensure a power reserve to increase grid stability. Renewable energy sources can also play a significant role as opportunity of a smart and sustainable mobility, where innovative storage systems and electrical machines represent challenging application fields [6-10].

In this scenario, this paper aims to provide an overview of the main technical and economic challenges towards the goal of 100% RES to fit the green transition.

II. DC GRIDS AND CONTROL STRATEGIES

Due to the recent increase in the use of DC for both generation (PV, FC) and storage (batteries, supercapacitors (SCs)) and the proliferation of DC loads, DC microgrids have gained popularity due to possible advantages with respect to traditional AC counterparts. Indeed, DC microgrids can provide a limited number of conversion stages and do not require reactive power or synchronization. On the contrary, the complexity of the DC bus voltage increases, as well as the power-sharing control [11]. As shown in Fig. 1, DC microgrids, which are connected with the main electrical grid through a bidirectional DC/AC inverter, are mainly composed of DER (PVs, wind turbines), ESSs (battery, SCs), DC loads and AC load, interfaced with the DC bus through unidirectional or bidirectional DC/DC or DC/AC converters.

The DC microgrids can operate both in grid-connected or islanded mode. In the first case, the DC/AC converter connected to the main grid controls the DC bus voltage, while in the islanded mode it is controlled by the ESSs, which are mainly composed of batteries and supercapacitors. Batteries have high energy density and can be used to compensate for low-frequency power mismatch, whereas, on the other hand, SCs have high power density and can be used to damp the higher frequency power fluctuation.

The PV system and wind turbines usually operate in Maximum Power Point Tracking (MPPT) mode and, when needed, can reduce the injected power. In grid-connected mode, both positive and negative power unbalance are handled by the DC/AC converter connected to the main grid. In islanded mode, the power unbalance is handled by the ESSs, which must be installed in sufficient quantity to ensure such operation.

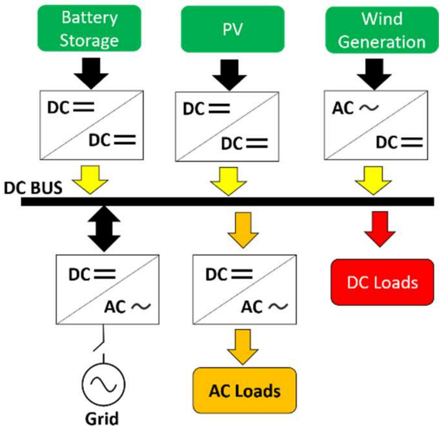


Fig. 1. Schematic of a DC microgrid.

In emergency conditions, if the ESSs cannot handle the power unbalance, some loads may be connected/disconnected to keep the bus voltage at the desired value. As summarized in Fig. 2, several control strategies can be applied to achieve the DC bus voltage control and the power sharing among the different sources and loads, which represent the key elements for the optimal management of DC microgrids.

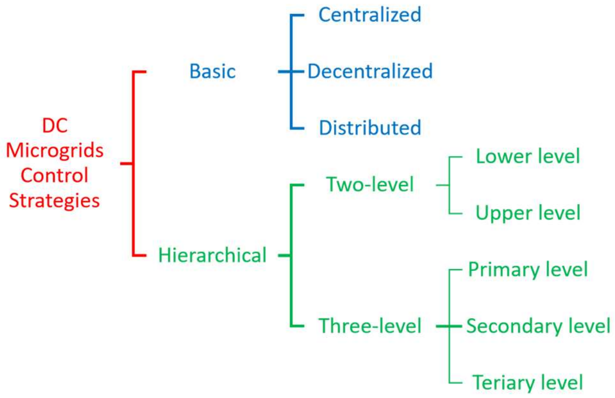
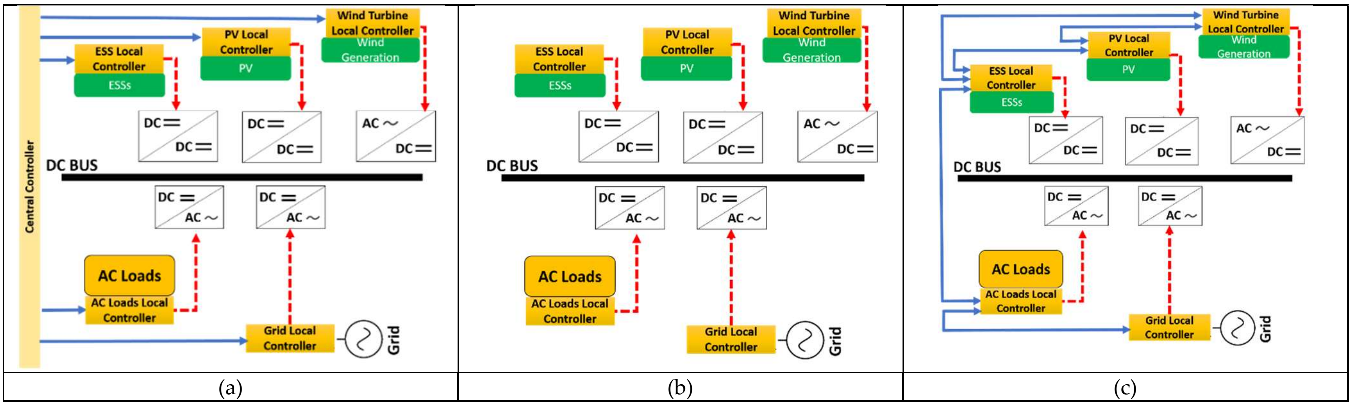


Fig. 2. Summary of the main control strategies for DC microgrids.

As shown in Fig. 3 (a), in centralized control schemes, a central controller collects data from all the units in the microgrids via a communication link. Based on different elements such as the total power generation, the total load consumptions and the microgrid operation mode, the central controller generates appropriate control signals, which are sent back to each Local Controller (LC) unit. The centralized control provides the best performance in terms of power sharing. On the other hand, it has poor reliability, flexibility, scalability and does not tolerate a single point of failure [12].



(a) (b) (c)

Fig. 3. (a) Centralized, (b) decentralized and (c) distributed control in DC microgrids.

In the decentralized control strategy, all units are controlled by an LC, leading to multiple local controllers, as depicted in Fig. 3 (b). Different quantities, such as input and output voltage and current, are measured and employed as input signals to the LC that generates the control signals for the PECs. The main advantages of decentralized control are fault tolerance, absence of costly communication links and ease of scalability. The drawback is the lower power sharing capability compared to the centralized control [12].

The distributed control strategy combines centralized and decentralized control (Fig. 3 (c)). The main difference is that the communication links are realized between neighboring units LC rather than having a central controller. The communication link is used to exchange information such as bus voltage, output current of DERs, State of Charge (SoC) of energy sources, etc. Thanks to the communication link, optimal power sharing capability can be achieved. Moreover, the distributed control scheme can tolerate some points of failure differently from centralized control. The main disadvantage of distributed control is the complexity of the system and the stability issue [13].

The Hierarchical control for DC microgrids is similar to the one for AC microgrids. The main objective of the hierarchical control is to optimally coordinate the ESSs, the DERs and the loads using three control levels namely primary, secondary and tertiary.

The primary controller corresponds with the Local Controller. The locally measured quantities are used as input variables of the controller, in order to keep the DC bus voltage constant and achieve power sharing. The primary controller has a faster response time, whereas the secondary controller oversees compensating for the residual DC bus voltage error. Moreover, it attempts to lower the power unbalance by appropriately allocating power among available DERs: the secondary controller is slower than the primary one. Finally, the tertiary controller's main task is to keep a stable, efficient and economic operation of the DC microgrid. The tertiary controller has the slowest response time [13].

For a safe, reliable and cost-efficient operation of the DC microgrid, several issues must be addressed and solved. Power and load sharing, voltage stability, loss reduction, power flow control between multiple DC microgrids, economic efficiency and blackout mitigation are some of the main challenges to be faced in the next future [13].

III. HYBRIDS GRIDS AND POWER MANAGEMENT STRATEGIES

A hybrid AC/DC microgrid is composed of both DC and AC sub-microgrids, interfaced by a bidirectional InterLinking Converter (ILC), as shown in Fig. 4. The DERs or ESSs can be connected to both sub-microgrids. This structure can provide easier integration with both the AC and DC-based DERs, ESSs and loads, reducing the number of conversion stages and increasing, therefore, the reliability, efficiency and flexibility. Nevertheless, such a system increases the complexity of the network structure and it requires synchronization and interconnection of different power converters [14].

An example of a hierarchical control scheme for hybrid microgrids is shown in Fig. 4. Similar to AC and DC microgrids, it is layered into the following three levels:

1) Primary control: the primary controller locally regulates the DC bus and AC grid voltages and frequency in the desired range. The active and reactive power injected and absorbed by each unit is controlled to achieve power sharing. Depending on the microgrid operation mode, different control strategies are chosen for the PECs: in grid-connected operation, the utility grid maintains stable voltage and frequency while the microgrids PECs are operated in the grid-following mode for maximum power generation. In islanded mode, when the microgrid is disconnected from the utility grid, one or more DERs operate in grid forming mode and ESSs operate in discharging mode.

2) Secondary control: the DC bus voltage error in the DC part of the microgrid and the AC grid voltage and frequency in the AC part of the microgrid are compensated by the secondary control.

3) Tertiary control: the tertiary control is enabled only in grid forming mode; its main task is to regulate the power flow between the hybrid AC/DC microgrid and the main electrical grid, to ensure high power quality, high efficiency and economic operation.

The power management strategies of hybrid microgrids can be classified into three categories, as highlighted in Fig. 5: Grid-connected mode, Islanded mode and Transition Mode.

In grid-connected mode, the control of power, voltage and frequency can be achieved in two ways:

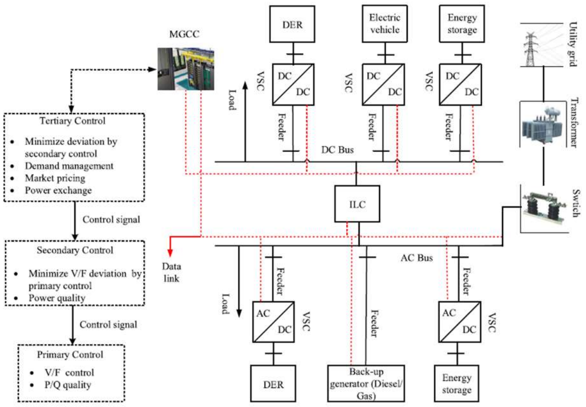


Fig. 4. Example of a hierarchical control scheme for hybrid AC/DC microgrid [14].

1. Dispatched output power mode: the hybrid AC/DC microgrid and the utility grid can exchange power. In this mode, DERs and ESSs can operate in current control mode or in voltage control mode. In the first case, the reference power is tracked by controlling the DERs output current, whereas the voltage and frequency are determined by the utility grid. Contrariwise, in voltage control mode the DERs output power is regulated by controlling its output voltage and DERs operate as synchronous generators. The bi-directional ILC can control the AC sub-microgrid voltage and frequency, the DC sub-grid voltage, or the power flow between the sub-microgrids.

2. Undispatched output power mode: the hybrid AC/DC microgrid does not dispatch power. In this case, all DERs in AC and DC sub-microgrids operate in current-controlled mode, thus injecting power into the utility grid. The ESSs are in charging mode and the ILC regulates the DC sub-grid voltage.

In stand-alone mode, DERs, ESSs and ILC need to be properly controlled to regulate AC microgrid bus voltage and frequency, DC bus voltage and power flow. In general, DERs and ESSs on the DC sub-microgrid control the DC bus voltage, the DERs and ESSs on the AC sub-microgrid control the AC bus voltage and frequency and, finally, the ILC controls the power flow between the sub-grids.

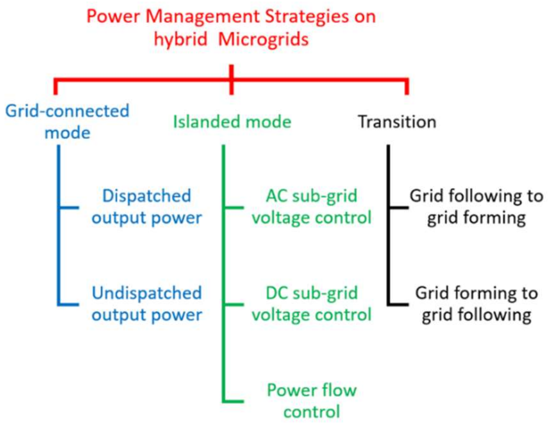


Fig. 5. Classification of the power management strategies of hybrid microgrids.

These management strategies are employed in steady-state operations. The transition between the two modes should be as fast and smooth as possible and should avoid voltage spikes, voltage/frequency deviations and circulating currents between DERs [15]. The Grid-following-to-grid-forming can be achieved in two ways:

a. An islanding detection algorithm gives the trigger to switch the controller from the current/power control mode to voltage control mode. For a smooth transition, the DERs line current can be first forced to zero or, for a faster transition, proper coordination between current and voltage control is implemented.

b. A unified control strategy for both grid following and grid forming modes is implemented. In this case, no islanding detection algorithm is needed. Smaller DERS and ESSs are operated in current control mode, whereas large DERs and ESSs are operated in current control mode.

On the other side, the grid-forming-to-grid-following transition can be achieved in two ways:

a. A synchronization algorithm should be used to make sure that microgrid and utility voltage are correctly synchronized. Then the controller switches from the voltage control mode to the current control mode.

b. A unified control strategy for both grid following and grid forming modes is implemented. In this case, no synchronization algorithm is needed

For a safe, reliable and cost-efficient operation of a hybrid AC/DC microgrid, the following issues must be addressed and solved:

- balanced load-sharing among Distributed Generators (DGs) according to their capacity;
- equal harmonic current sharing among the DGs;
- stable transition of operating modes;
- synchronization with protective elements;
- maintaining constant terminal voltage and frequency within the prescribed limit..

IV. HYBRID ENERGY STORAGE SYSTEMS IN MICROGRIDS

In microgrids, the ESSs usually exhibit irregular and frequent discharging/charging patterns, which truncates their lifespan. Therefore, the replacement cost of the ESS increases significantly. Fig. 6 shows the power density vs energy storage capabilities for different ESSs: it can be noted that high energy density storage technologies, such as batteries and fuel cells, have limited power capability, whereas high power density technologies, such as supercapacitors or flywheels, have limited energy storage capability. It is, therefore, crucial to identify a hybrid system capable of providing both high-power and high-energy storage features: the drawback of each technology can be overcome with the so-called Hybrid Energy Storage Systems (HESSs). Depending on the purpose of the hybridization, different energy storages can be used as a HESS. Generally, the HESS consists of high-power storage (HPS) and high-energy storage (HES), where the HPS absorbs or delivers the transient and peak power, while the HES meets the long-term energy demand.

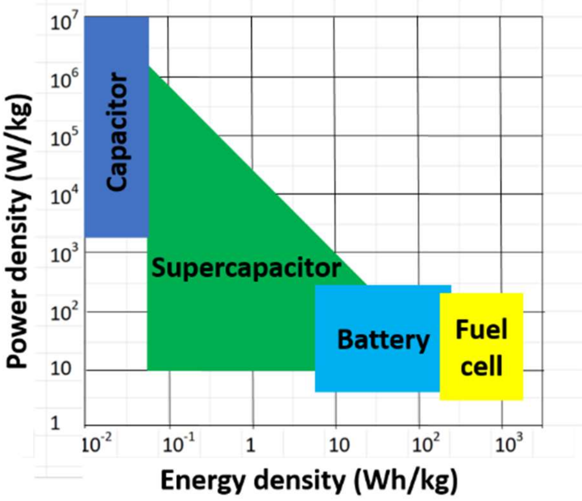


Fig. 6. Power density vs energy density capabilities of ESSs [15].

HESSs can provide many benefits for microgrids, including the improvement of the overall system efficiency, reducing the related costs and prolonging the lifespan of the ES. Due to the different types of energy storage technologies with different features, a wide range of energy storage hybridization can be formed [16].

For instance, in the case of employing both high specific energy storage (battery) and high specific power storage (supercapacitor), the energy stored within can be fully utilized in the best possible way, as shown in Fig.7. Indeed, if the load requires high power, both power flows will supply the load, whereas, in the case of low power requirements, the primary flow will be directed from the high specific energy storage to the load and, in the meantime, the secondary flow will recharge the high specific power storage, if needed. Moreover, in the case of negative power, the primary flow will be directed from the load to the high specific power storage, while the secondary flow will recharge the high specific energy storage from the load.

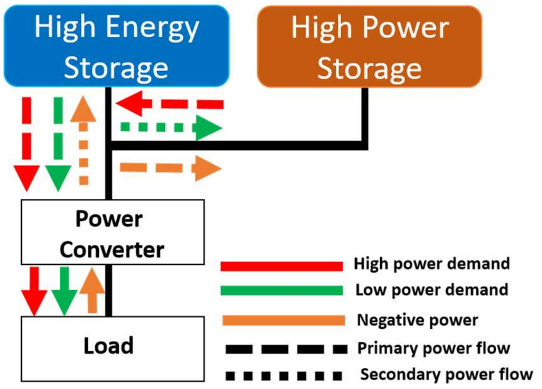
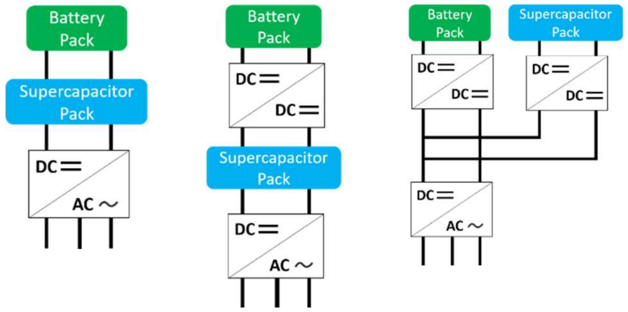


Fig. 7. Power flow in HESSs.

HESSs can be classified as passive, semi-active and active [17]. Passive HESSs interface the different storage systems directly, without using additional converters, as schematically shown in Fig. 8 (a). This solution is characterized by the easiness of implementation, high efficiency and cost-effectiveness. On the other hand, since the terminal voltage of the storage is not regulated, the power flow management is determined by internal resistance and voltage-current characteristics. As a result, the available energy from the HPS is very limited and it acts as a low-pass filter for the HESS.

In the semi-active topology, shown in Fig. 8 (b), a first power converter is inserted at the terminals of one storage, while a second one is directly connected to the dc bus. In such a system, the power flow management is improved, even if the use of one converter requires extra space and increases the overall cost of the HESS [18].

Finally, in Active HESSs (Fig. 8 (c)), each energy source is connected through a power converter to the system. In this case, the complexity, the cost and the overall losses of the system increase, even if the power flow is fully controllable, leading to excellent management [19]-[22].



(a) (b) (c)

Fig. 8. Classification of HESSs: (a) passive, (b) semi-active and (c) active.

V. CONCLUSION

In this paper an overview of the main challenges and solutions towards the technological transition to an electrical system with 100% renewable energy sources has been provided. The increasing use of distributed generation plants and the related static power converters, not able to provide inertia and damping, can notably degrade system stability. Therefore, the concept of "Smart Inverter" represents a promising solution to overcome this issue. In addition, innovative energy storage systems and hybrid solutions play an important role to ensure a power reserve.

Among the possibile solutions, DC grids, hybrid grids and hybrid Energy Storage Systems in microgrids have been investigated in this work, along with the related control and power management strategies.

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