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The Role of Renewable Energy System in Reshaping the Electrical Grid Scenario

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ABSTRACT Renewable Energy Systems have been in the spotlight of the academic and industrial research for more than two decades, thanks to the development of several fields related to the Electrical Engineering. More recently, with the increasing complexity of the individual renewable energy systems and the interconnection to the grid, the scientific panorama has been witnessing to a convergence of different topics, which span across several IEEE-IES thematic areas: power electronics, electrical machines, smart grids, energy storage, transportation electrification and aerospace. After a brief overview of the renewable energy technologies, this work deals with how the convergence of multiple technologies developed to provide marginal support to the grid has evolved into the foundation of the future utility grid and expanded to transportation sector. It will be shown how the design of a renewable energy system cannot prescind anymore from the electrical grid and from the ancillary services that are requested. Example of convergence are given for a smart transformer application and for a transportation application.

INDEX TERMS Photovoltaic, wind energy conversion systems, maximum power point tracking, power electronics, storage.

I. INTRODUCTION

Renewable Energies (RE) is one of the fastest growing sectors worldwide, with solar and wind technologies having registered the greatest increase in the last few years. According to Eurostat's yearly report [1], between 2007 and 2017, the share of electricity generated in Europe from low carbon Renewable Energy resources grew from 14.2% to 29.9%. Over this 10-year period, solar power contributions to overall electricity generation increased greatly from 0.1% to 3.8%, while contributions from wind increased 3.5 times, reaching the 11.4%.

The share of renewables will surely continue to increase. In December 2019, the European Commission presented the European Green Deal, an ambitious package of measures that candidates Europe to become the world's first climate-neutral continent by 2050 [2]. These efforts intend to maintain Europe into a leadership role in renewable energy policies, which has

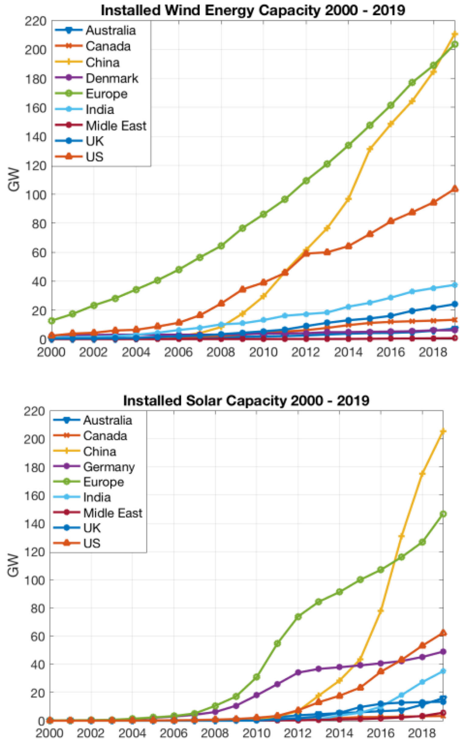

FIGURE 1. (a) Cumulative installed wind energy capacity, including both onshore and offshore wind sources, measured in gigawatts (GW) 2000-2019. (b) Cumulative installed solar capacity measured in gigawatts (GW) 2000-2019.

gradually shifted to Asia over the last decade. In China for instance, investments in renewable technologies have increased from 3 billion USD in 2004 to 103 billion USD by 2015 (an increase of 3400%), making the country the largest single financier in renewable technologies, investing approximately the same as the United States, Europe and India combined [3].

As a result, electricity generated from renewable energy sources has grown worldwide during the period 2008 to 2018. In 2018, China reached a peak of 184.70 GW of installed wing energy capacity, followed by the US with 94.30 GW and European countries (as shown in Fig. 1(a)). The total European installed wind capacity was still the highest in 2018, with, however, a lower trend, which suggests a significant overtake of China in the coming years. China has also experienced the fastest growth in installed solar capacity, with a decisive increase in the three-year period 2015-2018, followed by Europe, with Germany leading, the United States and India (Fig. 1(b)) [4].

Renewable Energies forecast is positive also for 2020. The *Global Energy Review 2020 of International Energy Agency* reveals that, despite COVID19 outbreak, the global use of renewable energy in all sectors increased by about 1.5% in the first quadrisect of 2020 compared to the previous year. Renewable electricity generation increased by almost 3%, mainly because of new wind and solar PV projects completed over 2019 and because renewables are generally dispatched before other sources of electricity.

Among the other renewables, photovoltaics is foreseen to be a pillar in the transition toward a greener energy system. Solar PV is set to increase the fastest of all renewable energy sources in 2020, with one-fifth of all renewable capacity deployed globally consisting of individuals and small-to-medium-sized enterprises installing solar PV panels on their roofs or business sites [5].

This scenario is expected to change radically the structure of the future energy distribution grid, passing from a centralized structure, with big energy plants delivering electricity to industrial sites and residential compounds at kilometers of distance, to a distributed structure, where the energy is produced from low, medium capacity renewable sources and consumed mainly locally.

As renewable sources are extremely variable, this reflects on serious issues that may affect grid stability. Grid standards have been continuously updated over the last few years, in many different countries, to cope with the constantly increasing renewable energy penetration rate in the grid.

According to the EU2050 roadmap [1] the actual goal is to reduce by 80% of the greenhouse gas (GHG) emissions by 2050. The target sectors, which are nowadays contributing to a vast share of the GHG are: Energy Production, Building, Industry and transportations. Whereas the renewable energy sources can help in the reduction of the GHG regarding the energy production, the technology developed for their exploitation and their usage has outgrown the initial aspect of energy production, and they are becoming the founding technology for the future electrical grids.

To keep pace with the growth rates of the last few years, technologies have evolved rapidly as well [6], with the reducing trends of cost and size for all scales (residential, commercial, utility) and an increasing trend of installed power and efficiency [7]. Many efforts have been made in industry and academia to proposed new, more efficient and reliable solutions to source, manage and dispatch energy produced from renewables. This paper is divided into two main areas: the first is review the latest updates on renewable energy sources technologies in terms of solar, wind and marine systems, with an eye to the sources, components and infrastructure. In the second part it will be shown how the usage of renewable energy technologies is reshaping the electrical grid paradigms.

II. PHOTOVOLTAIC ENERGY SYSTEM

Photovoltaic systems have been one of the first renewable energy sources to be exploited with a strong usage of power electronics components. Several aspects of the modelling will be analyzed in the next sections, which are of particular interest for higher voltage systems, where the series connection of several panels is needed. The modeling of the PV system is also an important aspect to perform on-line diagnostics for the strings [8].

A. THE PV STRINGS AND MISMATCHING PHENOMENON

Small PV installations are formed by series-connected panels, named strings, which are used to provide the high voltages

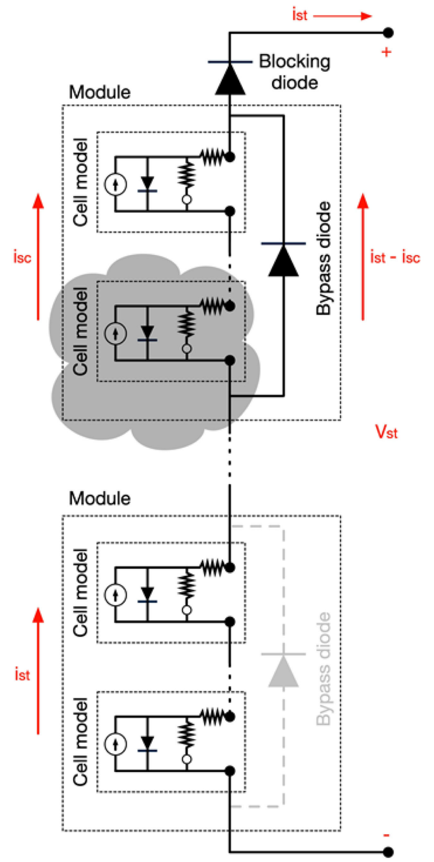

FIGURE 2. String structure.

needed for commercial inverters. However, such a series connection is exposed to the mismatching phenomenon [9], which strongly reduces the power generated by the PV string when multiple cells or modules are exposed to different operation conditions. Fig. 2 describes the electrical structure of a PV string, which is formed by the module cells, the bypass diode and the blocking diode. When the irradiance reaching a PV module is reduced by partial shades, both the PV voltage and short-circuit currents of that module are reduced. Therefore, the bypass diode becomes active when the string current, imposed by the highly irradiated modules, is higher than the short-circuit current of the shaded module; this action prevents high negative voltages on the cells forming the shaded module. This phenomenon has been modeled by [10] to predict the current and power generation of partially shaded PV strings using the single diode model and circuital equations. However, such a model was designed at the module level. Instead, the solution reported in [11] provides a detailed description of the modeling procedure for a PV string at the cell level. Such a model represents each PV cell using the Bishop model to account for the operation at the second quadrant under partial shading conditions. The string model equations are obtained applying the current Kirchhoff's law to the series-connected cells, then the voltage Kirchhoff's law is applied to the parallel connection of the cells and the bypass diode, which lead to the non-linear equation system representing each PV module. Then, both current and voltage Kirchhoff's laws are applied to the series connection of the PV modules and blocking diode, obtaining the expression for the relation between the string current and voltage. Finally, such a model enables to calculate the current, voltage and power of the string under partial shading conditions, but the model also provides the current, voltage and power on each cell of the string, which is useful to predict possible conditions leading to "hot spots" that could cause damages or even fire.

B. THE PV ARRAY

Larger PV arrays are formed by panels organized in multiple strings. The number of modules connected in series (length of the string) is calculated to reach the voltage required by the PV inverter (or load), while the number of strings connected in parallel depends on the power needed to be produced. The most common configuration adopted for PV arrays corresponds to a direct parallel connection of multiple strings, which is named series-parallel (S-P) configuration. Modeling the S-P configuration is commonly performed by modeling each string independently, adding the string currents for the same string voltages to calculate the array current. This modeling strategy has been used by [12] to predict the power generation of PV arrays based on the single diode model. Similarly, the cell-level string model reported in [11] is also extended to S-P arrays following that strategy. Therefore, such a solution is able to predict "hot spots" in S-P arrays, providing also an accurate prediction of the power generation.

However, the S-P configuration is highly susceptible to large power drops under partial shading conditions. Therefore, other array configurations have been proposed to mitigate the effect of the modules mismatching [13]. For example, the works reported in [14] and [15] analyze the performance of different array configurations, under common shading conditions, using the single-diode model and a circuital simulator. Some examples of those configurations are the Total cross-tied (TCT) and Bridge linked (B-L) architectures. The simulations show that the configuration providing highest power depends on the shading profile; however, those studies were limited to small, fixed PV arrays. In addition, it is possible to form irregular configurations that could provide higher power production for particular shading patterns [16], which could be useful for reconfiguration applications, where the PV array structure is modified during the day to mitigate the impact of changing shading patters covering the array. However, selecting the best configuration requires a model able to predict the power production of any array configuration. This problem has been faced by proposing the general model for PV arrays reported in [16], which is able to predict the voltage, current and power of a PV array with any configuration. Such a modeling approach divides the array into subarrays to form the current and voltage Kirchhoff's laws; finally, all those equations are integrated into a single non-linear system solved using numerical methods. The main drawback of that model is the adoption of the SDM instead of the Bishop or any other second quadrant model.

In conclusion, it is needed to develop new array configurations for reducing the impact of the particular shading patters covering practical PV installations. This requires developing a cell-level model for any irregular or regular array configuration to predict both the power production and "hot spots" occurrence. Moreover, a fast model for irregular arrays is needed to support reconfiguration processes, which could improve significantly both the profitability and safety of a PV installation subjected to partial shading: the model could predict the configuration providing the highest power, but the model will also help to avoid configurations in which "hot spots" could occur, improving in this way the safety of the PV installation.

III. WIND TURBINES AND WIND POWER PLANTS

Wind power is experiencing a massive development worldwide both for onshore and offshore applications. Onshore wind turbines are typically based on Doubly Fed Induction Generators (DFIG) employing a partial size power converter (around 30% of the generator rating) which allows variable speed operation in a reasonable range, fault ride- through capability and possibility of grid support (active and reactive power control, related to grid voltage and frequency). DFIG onshore wind turbines are equipped with gearbox to adapt the slow rotating axis of the blades to the faster rotating DFIG speed. While the type 3 wind turbines, based on DFIG dominate the onshore market, the offshore market is dominated by the so-called type 4 wind turbines which are based on a full-size power converter which completely decouples the generator and the grid. The type 4 wind turbine allows the use of synchronous generators which can have a large number of poles. The combination of multipolar synchronous generators and a lower frequency in the generator side (typically around 10-15 Hz) allow to reduce the gearboxes to a single-stage or even eliminate completely the gearbox of the wind turbine in the so-called direct-drive wind turbines. These solutions are very relevant for offshore applications, since the costs associated to operation and maintenance are much higher (related to the difficult access and rough conditions offshore). The gearbox is one of the critical components in terms of time of reparation when it fails, therefore it is convenient to simplify or eliminate it when designing the wind turbine.

Regarding research and development trends in wind turbines, we are seeing developments in the following directions: (a) Using generators with a large number of phases (9 or 12 for example) with different converter sections connected to each of them. This solution allows to have a more enhanced reliability and redundancy; (b) Using higher voltage level in the generator and the converter; (c) developing DC wind turbines with MV voltage output of several kilovolts, this can require the usage of Modular Multilevel Converters (MMC); (d) integrate energy storage with the wind turbine; (e) For very high power wind turbines, there is also interest in using superconducting materials in the generator, in order to reduce the overall weight of the generator and the nacelle.

Offshore wind power plants can be connected using different transmission systems, as shown in Fig. 3. Most offshore wind power plants are connected with AC transmission systems. In the case of remote connection of more than 100 km HVDC transmission is being used in some projects in the North Sea, using Voltage Source Converter (VSC) technology with Modular Multilevel Converters (MMC). Other alternative concepts (like diode-rectifier units) have been proposed by industry and academia.

Onshore and offshore wind power plants include a number of wind turbines. The power plant is required to provide a range of services to the grid where it is connected, including voltage and frequency support and active and reactive power control. Additional requirements are being discussed in some applications and will be certainly requested in future grid codes. These requirements include grid forming capability of the wind power plant, black-start, inertia emulation, power oscillation damping and fast frequency response.

While most onshore and offshore wind turbines are connected to a medium voltage AC collection grid, some research and development is done in the direction of developing DC collection grids for offshore wind power plants [17]. This would be especially (but not only) relevant for remote offshore applications where the transmission is implemented with HVDC.

IV. MARINE RENEWABLE ENERGY SYSTEMS

The potential of electric power generation from marine renewable energies is enormous. Ocean tidal and waves are being recognized as a resource to be exploited for the sustainable generation of electrical power. High load factors resulting from the fluid properties and the predictable resource characteristics make ocean tidal and waves particularly attractive for power generation and advantageous when compared to other renewable energies. They are particularly considered to be a promising renewable power source for coastal areas or some remote islands [18][19].

A. WAVE ENERGY CONVERTER SYSTEMS

Wave energy converter systems, where their different conversion stages are illustrated by Fig. 4, are specifically categorized by their installation location and power take-off system. Most developed systems belong to six types, namely: attenuator; point absorber; oscillating wave surge converter; oscillating water column; overtopping device; submerged pressure differential (Fig. 5).

In wave energy converter systems, the main attention has been directed at the most appropriate generator topologies. In this context, linear generators seem to be an interesting option as they allow a direct extraction of the energy (direct- drive converter), but they are not yet currently used in most of the developed projects. Different types of generators were investigated, where the main conclusion was that the transverse flux permanent magnet generator is a good candidate in terms of higher power density and efficiency, while the permanent magnet synchronous

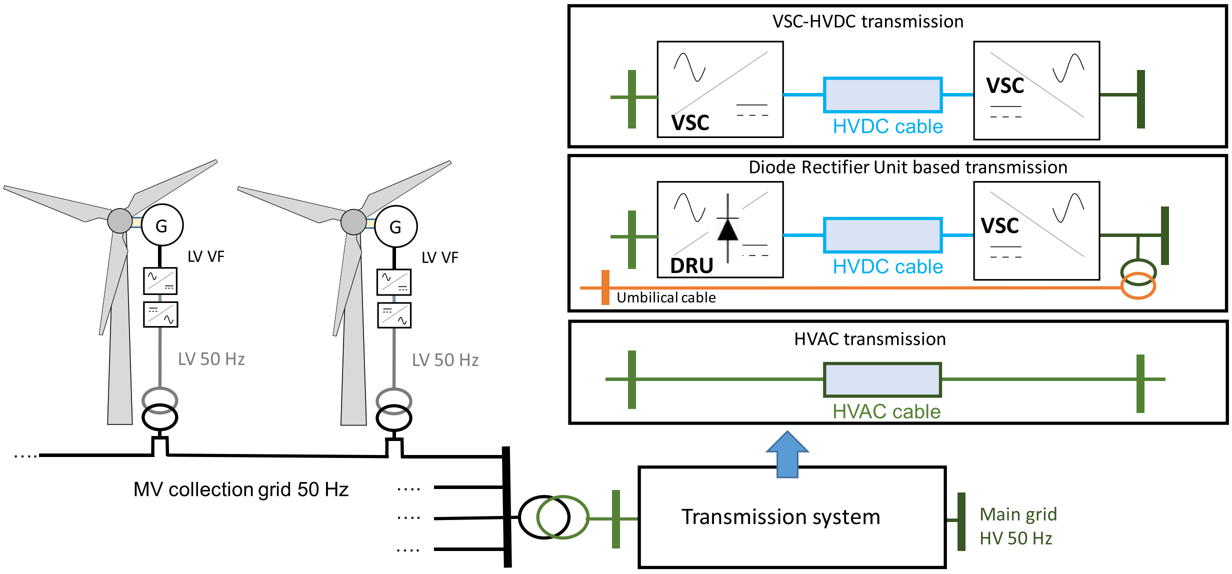

FIGURE 3. Possibilities for the transmission systems connecting Offshore wind power plants to main grid.

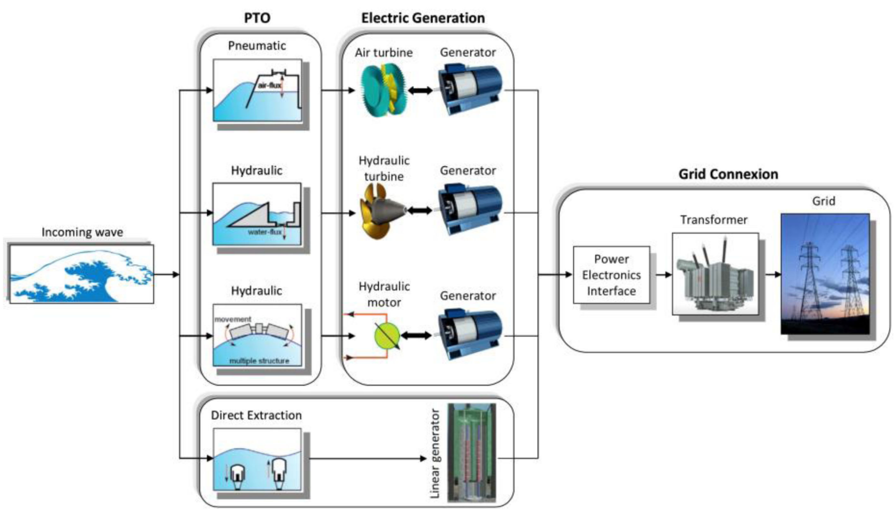

FIGURE 4. Wave energy conversion stages.

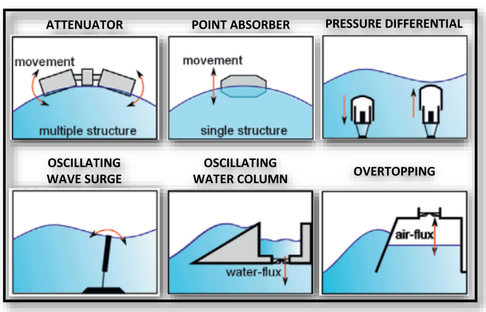

FIGURE 5. Wave energy converter systems concepts.

generator is an intermediate option. Induction generators adoption implies the use of a specific power take-off system induction additional mechanical losses affecting. In this context, there are still mechanical engineering challenges in terms of electrical generator offshore suitability.

An additional challenge facing the massive deployment of wave energy converter systems is the mooring. Indeed, its major requirements are withstanding the environmental and other loadings involved in keeping the device on station [20].

B. TIDAL STREAM TURBINE SYSTEMS

Harnessing tidal stream energy is generally made by means of horizontal axis tidal stream turbines which are submerged and they have to withstand high loading and harsh submerged conditions [21], [22].

Similarities between wind and tidal turbines led to the transfer of wind acquired knowledge and know-how acquired, which accelerate tidal stream turbine technologies development [22].

In terms of generator topologies, while the doubly-fed induction generator has been very successful for wind turbines, it will probably not be the candidate of choice for tidal stream turbine systems except if regular maintenance is possible. Direct-drive topologies using permanent magnet synchronous generators seem an attractive choice as in this case, the system cost increase is compensated by a higher amount of harnessed energy and lower maintenance constraints [23], [24]. However, drivetrain option choice is still a challenging task even if a geared generator seems to be the more appropriate in terms of reliability and cost-effectiveness for tidal stream turbine systems [22].

In terms of control and the related converter topologies, there are clear similarities with wind turbine systems [25], [26]. However, the swell effect during short-time periods, causes high tidal stream speed variations leading to strong fluctuations in the extracted power. This issue should be therefore handled with specific control strategies and appropriate storage systems (i.e., supercapacitors) to smooth the generated power before being injected into the grid [27], [28], [29].

C. CHALLENGES FOR MASSIVE DEPLOYMENT

In terms of competitiveness and massive deployment contexts, wave energy converter systems and tidal stream turbines are facing many constraints among them withstanding high loading and harsh submarine conditions. These constraints make these marine systems potentially suffering from higher failures rate. Evidence of this potential higher failures rate push towards adopting both resilient drivetrain topologies [22] and failure-resilient control strategies [30][31][32][33]. Another issue faced by wave energy converter systems and tidal stream turbines is corrosion and biofouling, which can, among others, increase weight and drag, thus significantly affecting the converter performance [34]. In this particular context, the condition monitoring system, in addition to his ability of failures detection and diagnosis, should be able to detect biofouling onset for maintenance scheduling [35], [36], [37].

Challenges that wave energy converter systems and tidal stream turbines should overcome to become competitive compared to wind turbines and PV generators should be: 1) withstanding extreme weather conditions leading to difficult and costly maintenance operations, 2) a specifically designed mooring systems (for wave energy converters) withstanding both waves/current/wind loadings and converter alignment constraint for capture maximization. In this context, fatigue is one of the key engineering challenges [18].

V. THE ROLE OF STORAGE

Direct integration of RES with the grid is challenging and brings various issues due to their intermittent nature [38]. In this scenario, the battery energy storage system (BESS) is a flexible solution to absorb and store excess power available with RES and deliver it when required [39]. BESS is used for various applications such as power balance, frequency and voltage control, dc bus voltage control, cost minimization, etc.

Coordinated control strategies are proposed for power balance under various operations using BESS in PV-battery-based hybrid microgrids [40][41]. The control provides dc and ac bus voltages and frequency regulation. Moreover, it provides balancing the power flows in the systems automatically under different operating circumstances, regardless of disturbances from switching operating modes, fluctuations of irradiance and temperature, and change of loads. A robust optimal power management scheme is developed for a hybrid ac/dc micro-grid in [42], where dc bus voltage control is facilitated by the BESS charge/discharge control strategy. A supervisory control scheme for the mitigation of voltage regulation issues in a ring DC microgrid is presented in [43] using BESS. The optimal operation and management of microgrid (MGs) in the presence of RES and storage devices is presented in [44] to minimize the total cost of the MG. A model to determine the robust optimal dispatch schedule for the microgrid with BESS is proposed in [45] to minimize the daily operating cost.

The BESS is mainly used to buffer out the low-frequency oscillations and compensate for the intermittency of renewable energy sources, requiring high energy density. They cannot be used in applications that require high power capability for a shorter duration. To provide the high-frequency component of power and also to supply or absorb the high-power transients, energy storage with high power density is required. Loads based on hourly average variations can be considered as low-frequency variations, whereas power transients that sustain for minutes, seconds, or milliseconds come under the high-frequency segment [46]]. The high power capability of super capacitors (SC) is exploited in pulse operating modes for portable power systems [47].

A real-time energy management algorithm in order to mitigate pulsed loads effects on system performance is proposed in [48] using BESS and SC. Objective of the algorithm is to manage the storage devices in real-time in order to maintain system stability and performance in the short-term operation and minimize the energy cost in the long-term operation. The dc-link voltage regulation under dynamic changes in load and source power variation is proposed in [49] using hybrid energy storage system of BESS and SC. A new energy management scheme is proposed in [50] for the grid-connected hybrid energy storage with the battery and the SC under different operating modes. This scheme provides effective power-sharing between the different energy storage systems, faster dc-link voltage regulation to generation and load disturbances, dynamic power-sharing between the battery and the reduced rate of charge/discharge of battery current during steady-state and transient power fluctuations, improved power quality features and seamless mode transitions.

There are several power electronics solutions to integrate BESS with the electric grid. Some of the widely used topologies are 2- level converter with transformer, three-level active NPC converter, three-phase half and full bridge converter, modular multilevel converter, etc. Depending upon the requirements of power and the voltage levels, appropriate configuration can be selected. Detailed review and

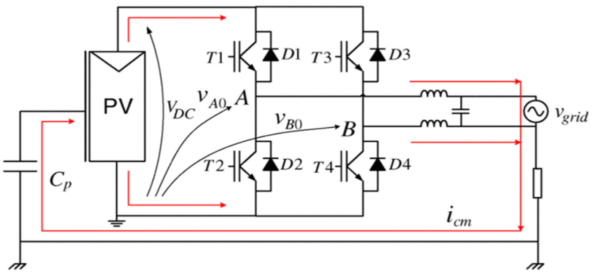

FIGURE 6. H-bridge topology for a photovoltaic inverter connected directly to the grid.

recommendations of power electronics system for grid connection of battery energy storage systems can be found in [51], [52].

VI. THE BUILDING BLOCKS OF THE RENEWABLE ENERGY SYSTEMS

The link between renewable energy and power electronics has always been one of the strongest. Indeed, the electronics has enabled the energy conversion from the different sources to a usable DC or AC supplies.

One of the major events in the late years of the 2000 was the incentives of the national and super-national governments for the installation of renewable energy systems. This has pushed the creativity and the engineering minds for the optimization of power electronics topologies specifically thought for photovoltaic or wind energy conversion systems.

The challenges of the applications were:

1) High efficiency with low-cost
2) Wide range of voltage conversion
3) Intermittent nature of the energy source

The pursuit for the high efficiency and the low cost pushed the engineers to remove as many components as possible, and the transformers that were guaranteeing the galvanic isolation and the voltage adaptation were among the first "victims" of this trend. However, by removing the transformer in a grid-connected system, the possibility for ground leakage current (i.e., common mode current) flowing into the electric grid became a reality. Consequence could range from a deterioration of the power quality to a complete inability to transfer the power to the grid, due to the tripping of the protection devices (Residual Current Device). A florid era of special topologies, which could work with a reduced common mode current, was therefore started.

The first topologies to be studied were based on the H-bridge, a standard topology for the Uninterruptible Power Supplies (UPS), connected to the grid through a filter (inductive or LCL), as shown in Fig. 6, where the DC source is supplied by a PV panel. In the figure, a capacitor Cp represents the distributed capacitance between the photovoltaic cells and the metal frame of the panel, which is ground-connected for safety purposes (indeed, touching an ungrounded frame would be at risk of electric shock). As can be seen, this capacitance closes a ground loop, composed of the grid and the ground connection. It must be said that different countries have different grounding systems, but the principle does not differ much. This ground circuit has a resonant behavior (due to the filter inductance and the panel capacitance) with a variable transfer function (the parasitic capacitance changes according to the humidity and other environmental conditions, shifting the resonant frequency).

Throughout the years, dozens of topologies have been proposed [53], among them, some major characteristics can be found [54]:

1) In the topology, some devices operate at high switching frequency, while others at line frequency (for the positive and negative half-wave of the grid voltage).
2) Hypothesis on the power factors are made, for example, many topologies assume unity power factor while considering the diode free-wheeling.
3) Mixed-type devices (MOSFET and IGBT) are considered, since MOSFETs exhibit excellent on-state resistance but they should be avoided for hard-switching applications that employ the body-diode.
4) Additional devices, or modified modulation strategies to reduce the high-frequency content of the common mode voltage are employed.
5) Filtering or active filtering of the common mode current can be employed.

Although the most commercially successful topologies are variations of the H-bridge, which is a Voltage Source Inverter (VSI), the limited voltage capability of these kind of power electronics can constitute a limit, considering the intermittency of the energy source. Especially for lower power, distributed power electronics, if the grid voltage is constant but the energy source has variations depending on the available power, boost or buck-boost topologies with low ground leakage current are necessary. Researchers have been active at studying other kind of topologies, as the Current Source Inverter [55], that allows a single-stage intrinsic boost.

The CSI features an inductor in the DC Link, instead of a capacitor. This gives the capability to realize a shoot-through state of three-phase bridge, which charges input inductor and therefore offers boost capability. This is particularly beneficial for photovoltaic inverters, since the inductor in series to the PV panels helps smoothing the current, improving the panel performance. Biggest disadvantage of the CSI topology is reduced efficiency, due to need of reverse-blocking devices, that are realized with MOSFETs and diodes in series. Researchers have been studying alternative topologies, as the CSI7 with improved modulation techniques [55], which offers improved efficiency, and also adoption of different kind of devices.

The CSI features an inductor as a source instead of a capacitor. A further development is represented by a generalization of this concept: the source network can be represented by an arbitrary combination of inductors and capacitors, giving the designer further degrees of freedom: the impedance source converters. In [56] a comprehensive classification of the source networks (with and without a transformer) is given. One of the most popular solutions

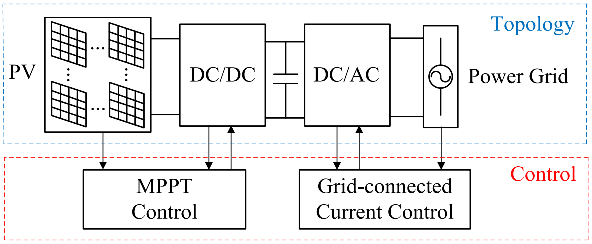

FIGURE 7. Centralized grid connected PV system.

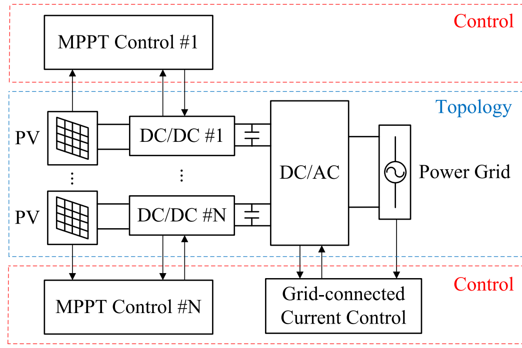

FIGURE 8. DC module grid connected PV system.

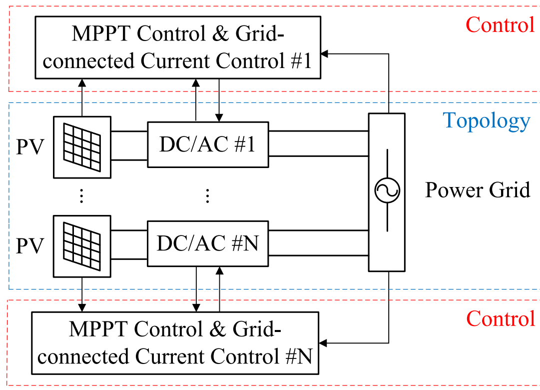

FIGURE 9. AC module grid connected PV system.

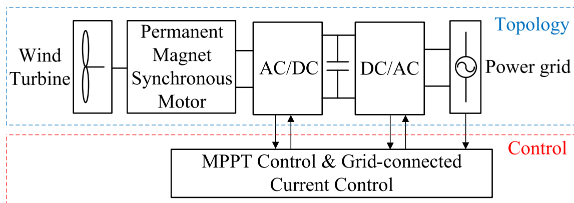

FIGURE 10. Permanent magnet synchronous generator based WECS.

for renewable energy systems is the three-phase Z-source converter, which offers low leakage current and buck-boost capability. The complexity of the topology and the quantity of the degrees of freedom makes it impossible to address them all in this overview paper, for a thorough analysis, the authors in [57] have analyzed the various possibilities.

Residential wind turbine systems usually feature passive rectifier and single- or three-phase power electronics, considering that the capacitive effects of the electrical machines are less than the PV panels, a conventional three-phase topology could be adopted. However, manufacturers often offer passive rectifier front-end to operate with turbines with appropriate MPPT and standard PV power electronics.

On-shore systems are usually connected through a 2-level or 3-level [58] converter (often in parallel) and a medium voltage transformer. Off-shore turbines require high-power converter solutions, depending on the type of collection, as previously described, including modular multilevel converters [59].

The grid connected PV system can be divided into two main categories based on the MPPT consideration, centralized MPPT (CMPPT) and distributed MPPT (DMPPT). For the CMPPT category, Fig. 7 shows its typical centralized grid connected PV system, which consists of many closely connected PV cells to form a PV array, a DC/DC converter and a DC/AC converter. The MPPT of the PV array is done by controlling the DC/DC converter, while the PV power is injected into the gird through the DC/AC converter. Both DC/DC and DC/AC converters are controlled by using pulse width modulation (PWM). The advantages of this topology are simple control, easy manage and lower system cost than the DMPPT case, but the main disadvantage is that significant power loss due to unbalanced generation among PV cells, thus leads to lower PV power conversion efficiency. The mismatch results from clouds, shadows, dust covering, etc. The centralized PV system has been proposed in both single-phase [60]–[64] and three phase systems [50]–[52].

For the DMPPT category, it allows local optimization and reduces power loss resulted from mismatch, in which it can sub-divided into DC and AC module grid connected PV systems as in Figs. 8 and 9. From Fig. 8, each PV cell/module is independently connected with a DC/DC converter, thus the MPPT for each PV cell/module is achievable. This topology improves PV system efficiency, but requires plenty of DC/DC converters, sensors and controllers, thus increasing the overall system cost. From Fig. 9, each PV cell/module is independently connected with a DC/AC converter for undertaking both MPPT control and PV power generation. This topology improves the PV system efficiency and does not require any DC/DC converter, which is widely used as micro inverters for achieving MPPT at single PV cell [25], [35], [36]. However, the control of the DC/AC converter is more complicated, and the overall system cost is still higher than the centralized PV system.

The wind energy conversion system (WECS) can be divided into two main categories based on the type of motor consideration, permanent magnet synchronous generator (PMSG) and doubly fed induction generator (DFIG).

Fig. 10 shows a typical PMSG based WECS, which consists of a wind turbine, a permanent magnet synchronous motor, an AC/DC converter and a DC/AC converter. When the wind turbine rotates, the synchronous motor is excited by permanent magnet to produce synchronous rotating magnetic field, then the three-phase stator winding reacts through armature

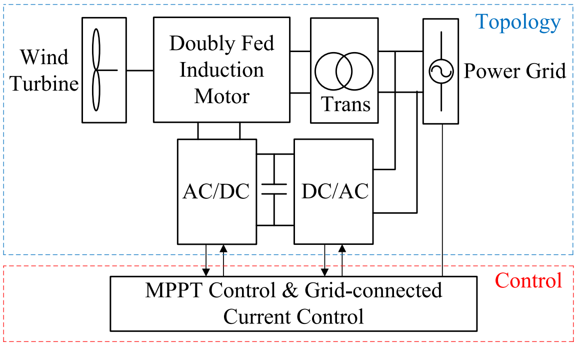

FIGURE 11. Doubly fed induction generator based WECS.

to induce three-phase symmetrical current. Thus, the kinetic wind energy is converted into electrical energy. Then the AC/DC converter will convert the motor three-phase voltage into a DC voltage. Finally, the wind power is injected into the gird through the DC/AC converter, where the MPPT control is done at the AC/DC converter. The PMSG based WECS has been further investigated for improving the efficiency, magnetic performance, etc. [68]–[72].

Similar to the operation principle of PMSG based WECS, Fig. 11 shows a typical DFIG based WECS, which consists of a wind turbine, a doubly fed induction motor, an AC/DC converter, a DC/AC converter and a transformer. The transformer is used for matching the stator voltage to the grid voltage. The DFIG based WECS has been further investigated for improving the efficiency and performance [58][73][74].

Due to the intermittent nature of the renewable energy, the development of the renewable generation technology focuses on the optimization of the power electronics converters and its control strategy in order to achieve:

1) High efficiency with low-cost.
2) Wide range of voltage conversion.
3) Ancillary services to the grid.

Apart from the two-level converters, the modular multilevel converter (MMC)-based topology is also a promising solution to integrate the large-scale PV system into MVac grid, as shown in Fig. 12 [75]. The three phases of this topology are identical, and each phase is composed of N inverter modules, which are connected in series at the MVac side and in parallel at a common LVdc. The topology allows the distributed MPPT, and the interleave technique reduces the current ripples.

The inverter module is composed by a full-bridge, and an interleave isolated dc/dc converter with three terminals, marked as t1 t2 and t3, respectively. Thanks to the common LVdc bus, the inter-module and interphase power unbalanced issues caused by the asymmetrical power generation from the PV panels can be effectively solved, as graphical explanation in Fig. 13.

The multi-terminal dc/dc converter is a different topology choice, which can provide more connectivity, e.g., electrical vehicle charging station and storage, was proposed in [76], as shown in Fig. 14.

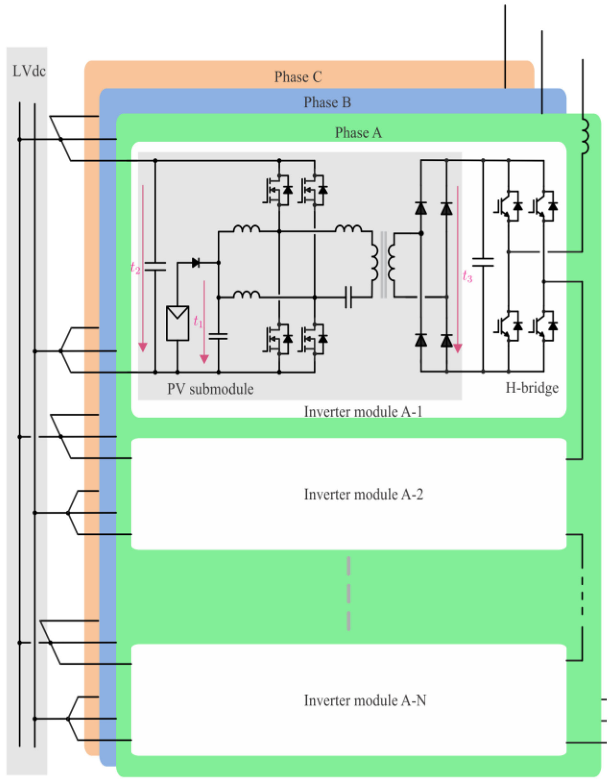

FIGURE 12. Half-arm MMC (star-configuration)-based PV system.

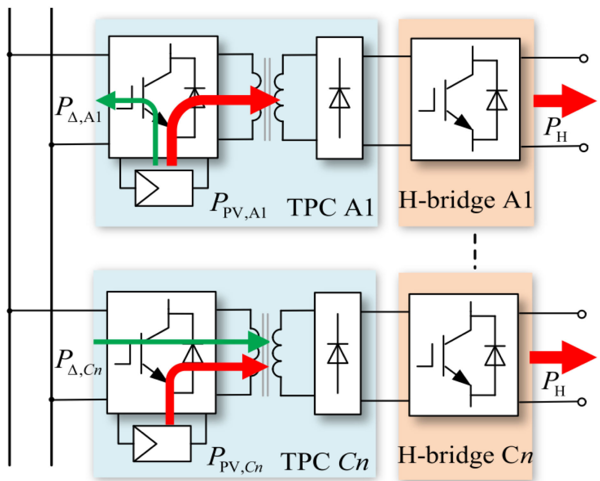

FIGURE 13. Graphical visualization of the inter-module and interphase power balancing principle.

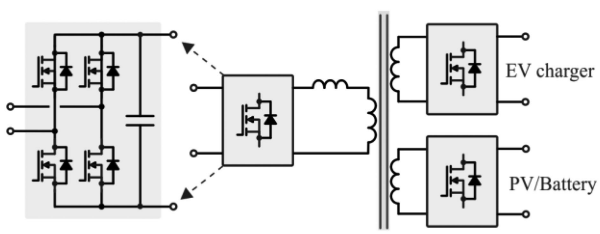

FIGURE 14. Architecture of multi-terminal dc/dc converter-based multi-sources integration.

VII. THE ANCILLARY SERVICES

The power electronics converters interfacing renewable energy sources (RES) into the electric grid are rated for the maximum capacity of the installed RES. Since the RES power output is lower than the installed capacity for most of the times, the power converter rating remains under-utilized. Various functionalities of power converters are explored in literature to improve its utilization. Recent grid codes require the support of reactive power along with active power delivery during grid voltage sag conditions and [77] proposes a scheme for the voltage support during voltage sag. During voltage sags, the controller generates the current references to maintain the dropped voltages within the grid code specified voltage magnitudes. This helps the system to improve the stability during voltage sags. Many voltage profile management strategies are proposed with reactive power injection and in low voltage grids with considerably higher R/X ratio, their effects are limited. In [78], the solar PV inverters are controlled in coordination with transformer tap changers for the low voltage grid voltage control. The unbalanced grid voltages are caused by faults in the power system and can cause the normal operation of DG converters and [79] proposes a control scheme to eliminate 3rd harmonic in output currents using an enhanced instantaneous active reactive control (IARC) technique. The work in [79] also reviews various methods available for the operation during unbalanced grid voltage conditions and advantages and disadvantages of methods such as positive-negative-sequence-compensation (PNSC), average active reactive control (AARC), etc. are listed.

Low voltage ride through (LVRT) capabilities are becoming mandatory in the medium and low voltage distribution grids and [80] proposes a method to provide ancillary services such as LVRT and anti-islanding protection schemes. The proposed method also helps in improving stability of system without the risk of unintentional islanding. In addition to voltage sag mitigation techniques, the voltage variation is common in distribution grids due to the load and generation changes. DG units are utilized to control the voltage variation by an adaptive slope voltage controller in [81]. This approach provides the transient performance improvement during different operating condition changes. The reactive power operating point changes depending upon the active power delivery of DG converters connected for wind energy conversion. [82] proposes a method to improve the reactive power injection capability when induction generating operating around synchronous speed. The maximum current is limited by the thermal limits of IGBT switches used for power converters.

When the DG converters are operated in islanded mode, active and reactive power sharing is important to feed the load at required voltage and frequency. The grids with a greater number of renewable sources lacks inherent inertia associated with synchronous generators. Operation as a virtual synchronous machine is an area which is being studied extensively in the RES based distribution grids. The authors in [83] proposes a method to emulate the operation of synchronous generator in a DFIG-based wind power generation to provide virtual inertia for the system. The virtual inertia concept works similar to the kinetic inertia of synchronous generator and it can be realized using the supercapacitor connected to the dc link or a rotating mass associated with DFIG. The proposed method does not use virtual inertia for power sharing and the method becomes more economical. The concept of alternating moment of inertia is utilized in [84] to stabilize the power system with DG working as VSG. The damping effect of the alternating moment of inertia is under investigation in this paper and the system performance has improved which leads to improved damping performance of the system during power system oscillations. Active harmonic filtering is important in the grid with a greater number of power electronic converters and non-linear loads. Current controlled DGs can be utilized to compensate the harmonic currents and [85] proposes a strategy to independently control harmonic and fundamental parts of current. The method proposed method is used without any phase locked loops and this eliminates any tracking errors associated with it. Along with the non-linear loads, the presence of power factor correction capacitors introduces the harmonic resonance. [86] proposes a selective harmonic compensation scheme based on modal analysis and this method improves the performance of the distribution system with DGs. A detailed model of the distribution system is used with DGs and power factor correction capacitors are used to verify the proposed algorithm. The ST can indeed be used in rural grids, where the with a reduced short circuit ratio is often present. Some of the possible services have been highlighted in [87].

VIII. SMART TRANSFORMER AND MESHED GRID OPERATION

Smart solid-state Transformer (ST) has been proposed to intelligently control and manage the modern electricity grid with high penetration of renewables. The ST can provide the MV and LV dc connectivity, which is convenient for renewable integration due to the less stage of power transformation. The availability of dc connection also allows to integrate storage elements like battery energy storage system (BESS) [87]. In Fig. 15, the performance of ST-based BESS during a symmetrical 40% voltage sag at the MVac grid are shown. In case the currents of the MVac/ dc stage in ST reach the rated value (5 A for the scaled down prototype), the BESS gets activated to feed the load with remaining power. The load and DG powers remain unaffected, when the DG is operated at MPPT.

The Smart Transformer concept belongs to a semi-centralized smart-grid paradigm, where the conventional power transformer is replaced by a controllable and smart element, which can provide services to the grid. A different paradigm is the decentralized one [88], [89], where the voltage and frequency control is embedded into each smart device in the smart-grid, which becomes capable of performing self-synchronization and power management. A hierarchical approach for the controls ensures that the rated values of voltage and frequency are reached as well as achieving the power exchange between different micro-grids.

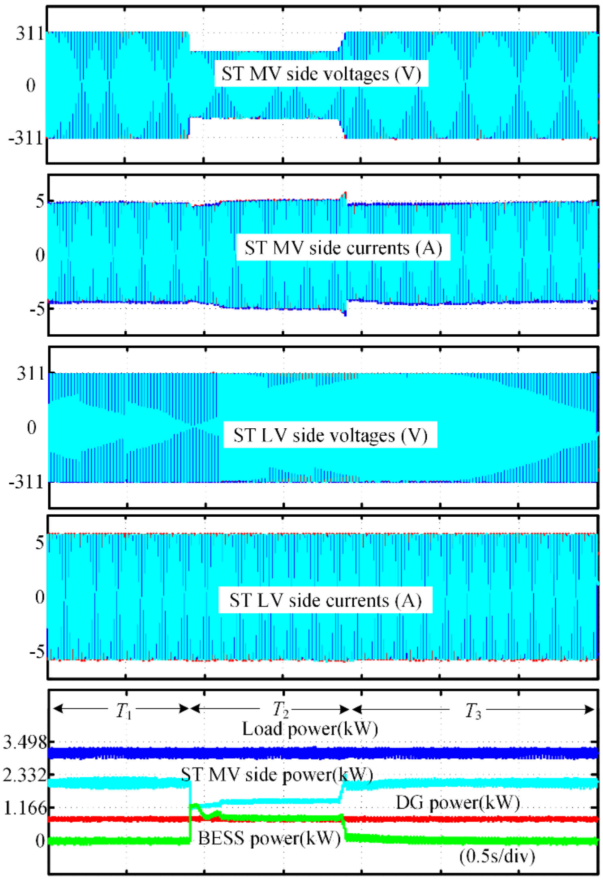

FIGURE 15. Experimental results of the ST-based BESS (time interval T1 and T3: normal operation, and T2: voltage sag).

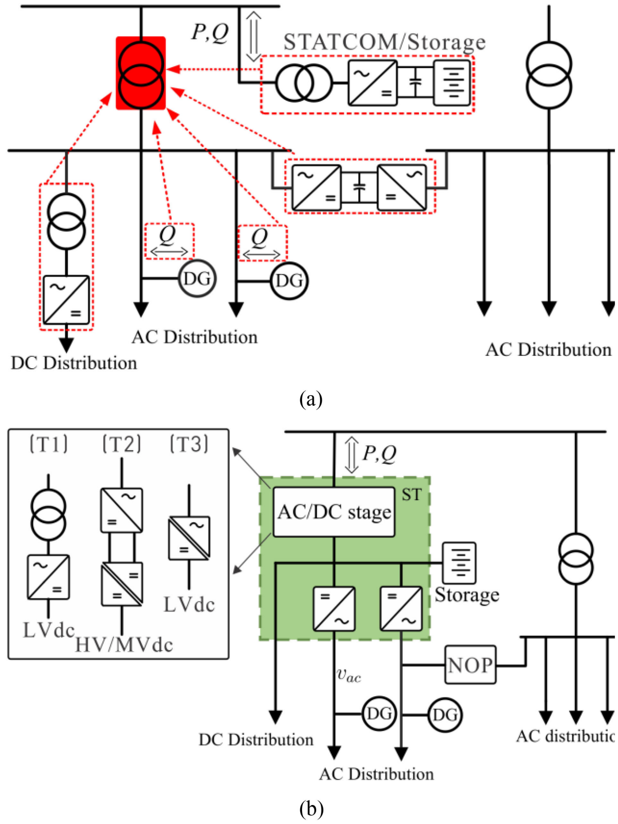

FIGURE 16. Modernization of electricity grid of the (a) current solution, and (b) ST-based solution.

A. MODERNIZATION OF THE ELECTRICITY GRID

Due to the electricity grids experiencing emerging challenges caused by the increasing penetration of renewables, the current electricity grids are pushed to be modernized, as shown in Fig. 16(a) [90]. The STATCOM (energy storage system) is needed to support the MVac grid voltage (compensate the intermittent nature of renewables). The electricity grids are meshed by a back-to-back converter to attenuate voltage violation or overloading of grid assets (cable and transformer). A low-frequency transformer plus a dc/ac inverter provides a dc distribution grid. Additional, distributed generators are required to provide the reactive power support. A smart energy management system is needed to coordinate the aforementioned distributed systems, resulting in dependence on communication technology and cyber-security issues.

In contrast, the single ST can provide the connectivity for the storage system and LVdc grid, and mesh the electricity grid easily by a normally open point, instead of extra installation of power electronics, as shown in Fig. 16(b) [91]. With respect to the specific requirements, three different architectures for the MVac/LVdc transformation are defined as T1, T2 and T3. In T1 and T3, the ST can only provide the LVdc distribution grid, while T2 can provide either the HVdc or the MVdc. In T1 and T2, the high/medium isolation technology is used while in T3 a low frequency transformer is adopted. Besides the aforementioned merits, the ST can also allow to operate the electricity grid in meshed or radial configuration, and switch between these two configurations with a smooth transition.

B. SMART TRANSFORMER-FED MESHED NETWORK

In case of ST-feeding a radial ac network, the ST can control the active power flow, provide reactive power support in the MVac grid, improve the power quality of MVac grid current and LVac grid voltage, stabilize the low ac grid, and also achieve communicate independent optimization and management of LV ac grid.

In case of ST-feeding a hybrid ac and dc network, apart from extending aforementioned services to the hybrid ac and dc networks, the ST can also optimize power flow between the LV ac and dc network to obtain various objectives (to minimize the power exchanged between the MVac grid and ST, to minimize the line losses).

The ST can further improve the electricity grid performances by flexibly meshing the electricity grid, due to the excellent power flow control capability of ST. The ST can mesh the ac grid at either the LVac busbar (highlighted in yellow) or the end of LVac feeders (highlighted in red), mesh the LVac and LVdc grid (highlighted in green) and mesh the

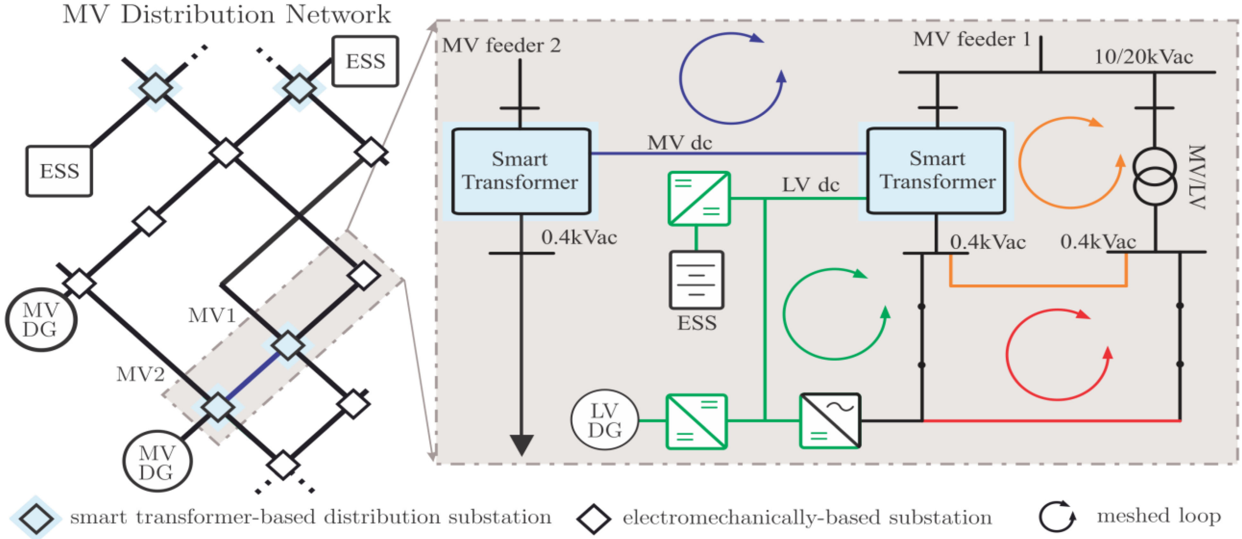

FIGURE 17. Configuration of the ST-based meshed network.

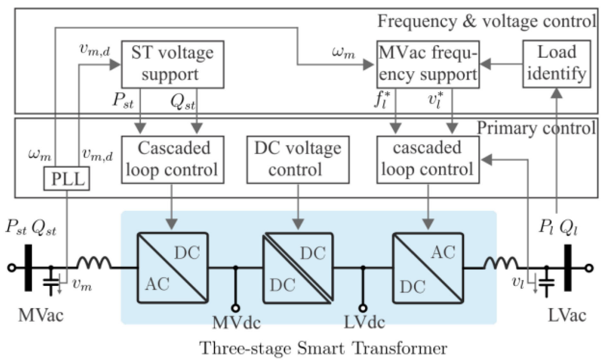

FIGURE 18. Frequency and voltage control via ST.

region grid through the MVdc line (highlighted in blue), as shown in Fig. 17 [92] .

In comparison with the ST-fed radial network, meshed grid operation can further increase power flow optimization capability and avoid the overloading of grid assets during healthy grid condition and can increase the system resilience and reliability as well in case of grid faults.

C. GRID VOLTAGE AND FREQUENCY SUPPORT

The ST can provide the voltage and frequency support for the MVac grid, and the system control block diagram of ST is shown in Fig. 18 [93].

A PLL is used to detect the MVac grid voltage amplitude and frequency. In case of MVac voltage amplitude variation, the ST voltage support control will adjust the output reactive power reference for the MVac/dc converter to regulate the MVac grid voltage amplitude. In case of MVac grid frequency variation, based on the load identification of the LVac grid, the corresponding frequency and voltage amplitude reference, which can quantitatively change the load in the LVac grid, are generated for the LVdc/ac inverter. Consequently, controlling

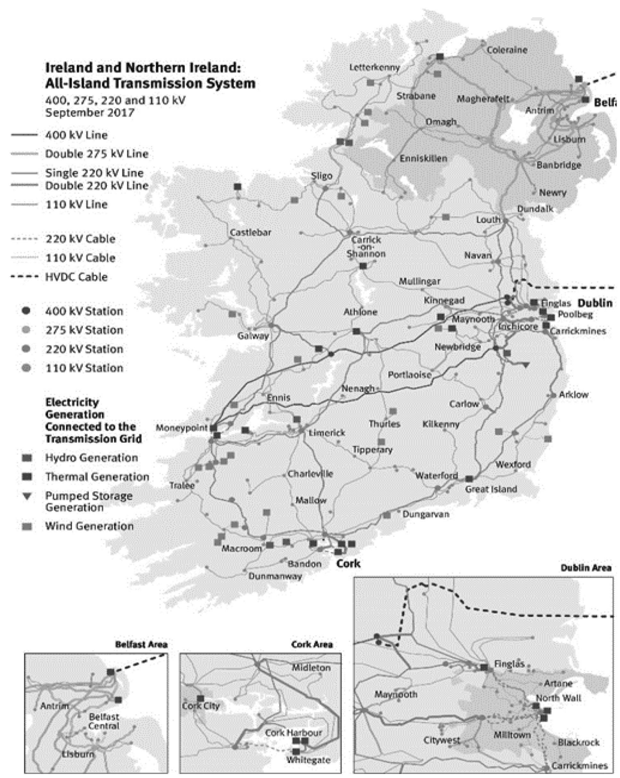

FIGURE 19. All-island Irish power system map (available at: www.eirgridgroup.com).

of the ST fed active load achieves the MVac grid frequency support.

Three cases of voltage/frequency control, as well as frequency stability and voltage stability in high wind power penetration are carried out in [93], based on Irish Transmission system as shown in Fig. 19, where 1479 buses, 1851 transmission lines and transformers, and 245 loads are included. The electricity consumption share includes 39.3% industrial,

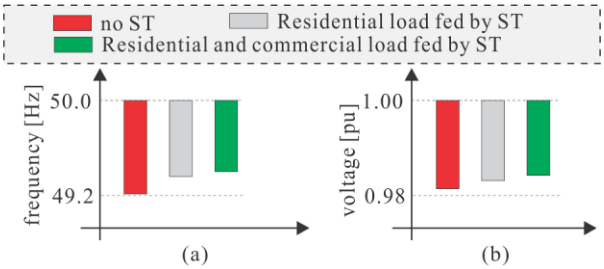

FIGURE 20. Results of case 1: maximum frequency and voltage sag at Dublin after a contingency.

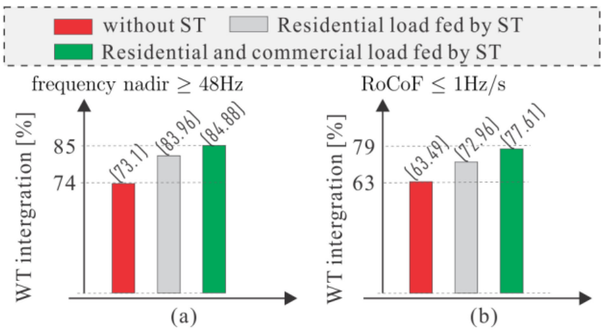

FIGURE 21. Results of case 2: maximum percentage of WT integration taking into account grid code of (a) frequency nadir, and (b) RoCoF.

31.4% residential and 26.9% commercial loads in 2015 [94]. The detailed data can refer [93].

For case 1, Fig. 20 shows the maximum frequency and bus voltage variation at the capital, Dublin, after a contingency. In case of the original grid without ST, both the frequency and voltage have maximum sag depths. With the increasing integration of ST, the frequency and voltage sag depths are reduced continuously, because of the provision of inertia by load control in the LVac networks.

For case 2, the maximum percentage of wind turbine (WT) integration is compared in Fig. 21(a) and (b), respectively, when the Irish grid code requirements on the frequency nadir (48Hz) and rate of change of frequency (RoCoF) (1Hz/s) are taken into account. As shown in Fig. 20(a), the ST can help to increase the percentage of WT integration from 73.1% to 83.96% and 84.88%, and Fig. 20(b) shows the percentage of WT is increased from 63.49% to 72.96% and 77.61% corresponding to the ST feeding residential load and additionally commercial loads.

For case 3, the voltage nadir in case of 50% and 70% WT integration is shown in Fig. 22. The ST can also reduce the voltage nadir.

IX. OUTLOOK TO THE FUTURE TRANSPORTATION APPLICATION

One of the major recent trends in the renewable energy has been the link with the transportation sector. Many people believe that the variability of the renewable energy sources could be used in conjunction to the storage distributed in

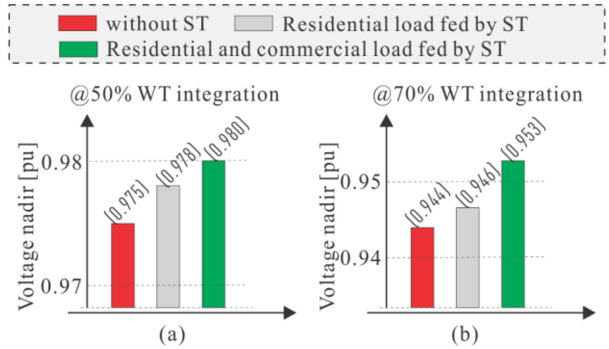

FIGURE 22. Results of case 3: voltage nadir when WT integration at (a) 50%, and (b) 70%.

the transportation means. Traditionally, the EV charging station is realized by a traditional transformer connecting to an ac/dc and a dc/dc converter in distribution grid as shown in Fig. 23(a). After grid restructuring by replacing tradition transformer with ST, the both MV and LV dc links of the ST can be used for integration of EVs. This scenario is shown in Fig. 23(b) and (c). The EVs can be either charged from the MVac grid or through the available DG power at LVac grid. Various power flow paths for the EV charging from different sources are shown in Fig. 24.

Efficiency curves for all the four ST based EV charging configurations, in addition to the traditional EV charging are drawn [92]. For drawing these curves, manufacturers data and the scientific literature [93][94][95] are used. Only for dc-dc conversion stage, SiC devices are used. It has been shown that that when the EVs have to be charged from the DGs then the EV should be connected to LVDC link of ST as it is more efficient compared to the traditional EV charging station (at least 1% more efficient than the traditional scheme). However, the MV dc link of ST should be the preferred choice of EV charging station when MV grid is utilized for the charging (at-least 1.5% more efficient). With more improvement in SiC and GaN based power semiconductor device technologies, there is possibility that the ST based EV charging station will have further improvement in the efficiency.

Another area of convergence between renewable energies and electric transportation is the aircraft sector. It has already been shown [96] that the pursuit for higher efficiency and reduction of maintenance cost has pushed the aerospace sector to turn towards more electric system on the aircraft. What was usually powered by hydraulic and pneumatic system is now powered by electric machines controlled by variable speed drives, making the aircraft a fully featured micro-grid with storage, generators and loads.

Indeed, many technologies that were born for renewable energy systems found their application in the aircraft. Power electronics solutions and control solutions proposed for RES and adopted in aircraft applications. An interesting convergence area is that, although the aircraft do not feature photovoltaic panels, the power electronics topologies and controls

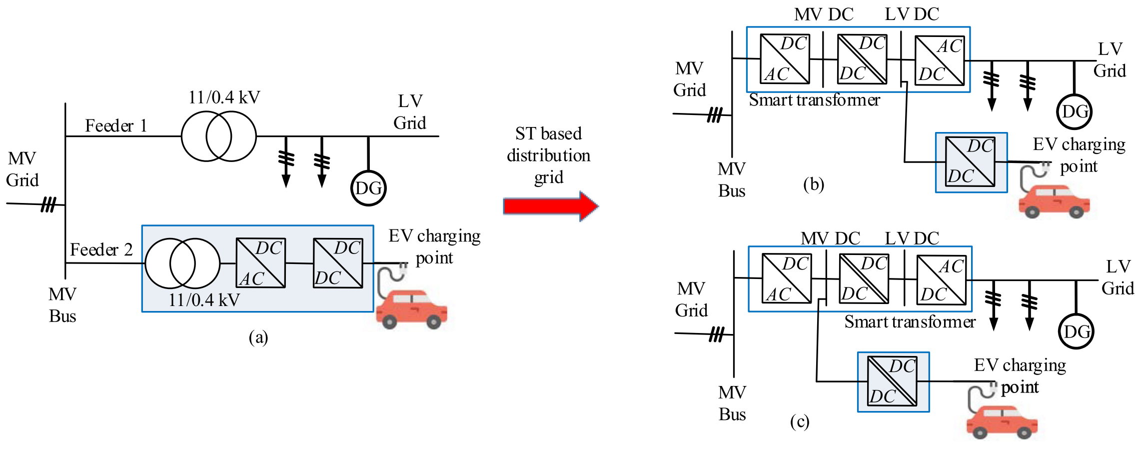

FIGURE 23. (a) Traditional distribution grid with loads and EV charging station supported by CPTs. (b) Restructured distribution grid with EV charging station supported by the LV dc link of ST. (c) Restructured distribution grid with EV charging station supported by the MV dc link of ST.

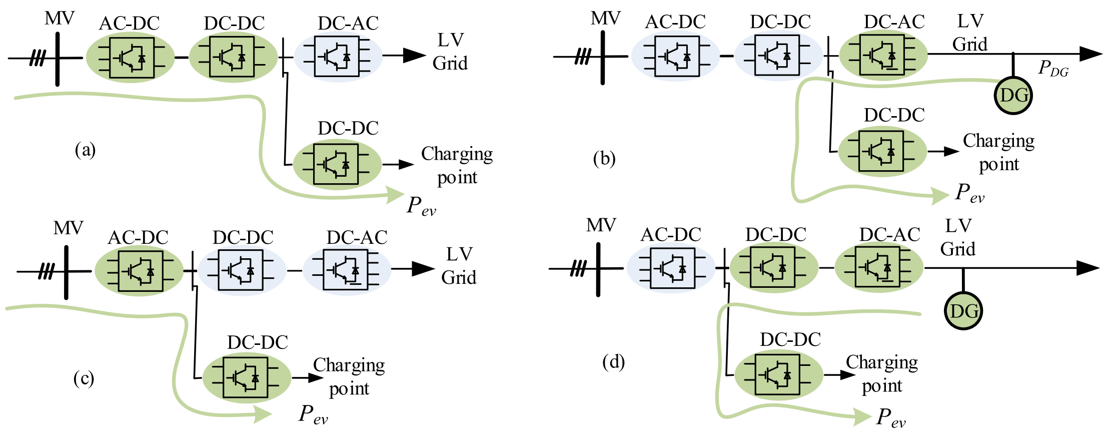

FIGURE 24. Power flow path during charging of EVs for different configurations. (a) Charging through MV grid. (b) Charging through DG. (c) Charging through MV grid. (d) Charging through DG.

proposed for PV systems (to reduce the leakage current) can find their application in a very different scenario.

1) Multiple port isolated dc-dc converters, born to interface photovoltaic sources, storage and the grid-connected inverter dc-link have been proposed for the usage as storage manager [95]] or as a power router [96]] or to improve system efficiency [97].
2) Photovoltaic Power Electronics inverters with reduced ground leakage current can be used as components of high-frequency dc-dc converters to reduce the conducted emissions and reduce the transformer insulation stress for the electrical power distribution of the aircraft [98].
3) Photovoltaics inverter can be used for high-reliability electrical drives to relieve bearing current and reduce circulating currents, especially when structures are made with new carbon fiber composite, due to the high common mode voltage variation [99].
4) Advanced energy management schemes with different targets can be applied to the aircraft systems [100].
5) The droop control scheme, applied in countless dc microgrids with mixed storage/energy systems, is one of the main control solutions for on-board electrical power systems in aircraft [101] and ships [102].
6) Where renewable energy systems have a predominant penetration in the electrical grid, the system stability can be challenged either by resonance or by the constant power load stability. This is also found in aircraft [103], which are fully power electronics networks.

In this framework, not only the aircraft itself, but also airports constitute a good platform for this convergence, since they spread over a wide area, perfect for photovoltaic panels, and the noise requirements are already relaxed, given the airplane noise, opening the possibility for wind turbine installation. According to [104], the airports which achieved the carbon neutrality use a mix of techniques, from increasing the energy efficiency of the building, to storing the snow as a coolant for the summer (Oslo Airport) to the employment of Biofuel (Stockolm), Photovoltaic (the biggest in Denver) and Wind Energy Systems (Galapagos). In the 14th 5-year plan of the China Civil Aviation [105] there is also a strong focus on the green aspect of the new airports. With the increasing trend of aircraft electrification (electric propulsion aircraft [106]), the electrical energy demand will increase:

1) All electric aircraft will require their storage systems to be charged, as well as the hybrid electric aircraft will need to recharge their backup batteries.
2) To save fuel as well to reduce the pollution, the More Electric Aircraft will use the airport electric grid to power the auxiliary systems while docked, avoiding turning off the engines.
3) Additional improvements in terms of electrical taxing and logistics will further increase the electric consumption.

All considered, the aircraft transformation will force a modification of the actual airports, which will need to provide additional power and an improved infrastructure similar to a micro-grid with renewable energy systems and storage.

Since the ST is a much more complex system than a conventional power transformer, there may be concerns regarding its reliability. However, the great level of modularity offered by the ST can be used for fault-tolerance and for advanced thermal control, with the capability of controlling on-line the reliability. Some of these controls enabled by the high levels of modularity have been reported in [107], [108]. The basic idea is to route the power arbitrarily between the parallel/series connections, according to the remaining lifetime of the components. In this way, if a good reliability model is available and the stress is estimated on-line, it is possible to optimize the maintenance scheduling [109].

Many of the technologies described in this paper are being implemented short-term. There are already some pilot projects for ST (LV-engine, to be delivered in 2022) [110], and the greener airports will be built in the near future. Considering the European Union, in the Horizon2020 framework, several projects have devoted efforts for the implementation of smarter electricity network [111] allowing for many technology demonstrators to be realized. The International Energy Association - Technology Roadmap: Smart Grids [112] foresaw the development of an evolutionary approach towards a decentralized energy generation by 2030, with the consumer/producer coordination by a widespread usage of the real-time energy data to continue until 2050.

X. CONCLUSION

This manuscript has dealt with the latest research topics on Renewable Energy Systems and has highlighted the future areas of convergence to different realms, including electric transportation, electric power systems, solid state transformers and electric aircrafts. In fact, the renewable energy systems have evolved from a simple grid supporting element, to the foundation of the future grids. The power electronics design, once tailored for the basic requirements of the application (solar, wind, maritime), now has to provide ancillary services to guarantee voltage and frequency stability to the grid. The convergence of transportation applications (and their need of charging) is further transforming this scenario, making it mandatory for a more intelligent grid, supported by power electronics designed specifically for this task, as the Smart Transformer. Large system, as aircraft or ships are also featuring a great extent of electrical system, that act as an isolated grid with similar techniques to the ones developed for the utility grid. These transport system, once connected to the mains, also need to interact with the grid intelligence in a coordinated way, further fueling the convergence of different systems and the demand for more intelligent designs.

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