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Unlocking the Hidden Capacity of the Electrical Grid through Smart Transformer and Smart Transmission

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Abstract—Power systems are experiencing a rapid and dramatic transformation driven by the massive integration of non-dispatchable renewable energy sources such as wind and solar and highly variable loads such as electric vehicles and air conditioning. This challenges existing grid assets eventually leading to update them which in turn increase significantly the costs of the sustainable technologies. Power electronics is a pivotal technology for electrical power processing for renewable energies and sustainable transportation. By means of "smart" functionalities power electronics converters already embedded in such applications, can also contribute to guaranteeing the overall system stable operation. Anyway this cooperative contribution from distributed devices may be not enough leading to the need in the voltage transformation and power transmission of "system level" power electronics solutions. In the case of large charging stations a Smart Transformer while in the case of large solar and wind parks integration Medium or High Voltage Direct Current Transmission are system level solutions. This paper wants to review the potential of using such infrastructures to increase the capacity of existing grid assets avoiding or deferring their upgrade and hence reducing the overall costs of renewables integration and of the electrification of transport sector. In fact the power converters embedded in **Smart Transformer (ST)** and **High Voltage Direct Current (HVDC)** can provide fast frequency and voltage response and precise control of power flow acting at system level much more effectively and feasibly for system operators as the distributed power converters embedded in several small sources and users. This paper reviews for the first time these two key power electronics "system level" solutions together - Smart Transformer and High Voltage Direct Current - starting from their basic functionalities and showings how they can go beyond them showing how with grid forming functionalities they can offer new "Smart Grid" tools to enhance the capability of the existing electric grid infrastructures.

Index Terms—Power electronics, smart transformers, high

voltage dc transmission, power system regulation, electrical grid stability.

I. INTRODUCTION

Electrical grids are suffering large demand variability caused mainly by highly variable loads such as air conditioning and electric vehicles [1]. The broader integration of renewable energies such as wind and solar is expected to worsen the situation resulting in further congestion and underutilization of the electrical network [2]. Most of these loads and energy sources are connected to the grid by using power electronics converters.

However during the last years, it has been registered not only a steadily increasing number of distributed power electronics converters but also "system level" power electronics converters have been embedded into the electrical grid to perform a multitude of tasks, as shown in Fig. 1. Due to the fast dynamical response of currents and voltages, these converters are used in a STATic COMPensator (STATCOM) to control reactive power, maintaining the voltage amplitude at a given level and increasing the transmission capability of the lines. Also, they are employed to manage Energy Storage Systems (ESS) to inject active power providing fast frequency regulation. High Voltage dc (HVDC) systems offer a cost-effective solution for long-distance bulk energy transmission. Smart Transformers (ST) provide voltage level transformation and a wide variety of ancillary services such as reactive power compensation, harmonic filtering, voltage sag compensation, frequency regulation, dc grids, among others [3].

Despite distributed and system-level power converters have become an essential component of power grids [4], they are usually associated with the reduction of system inertia, sub-synchronous oscillations, and other problems. Recent analyses show that a change in the control strategies can attenuate these issues allowing to take real advantage of the controllability and flexibility power converters bring to the electrical grid [5].

Power electronics-interfaced renewable energies, such as wind turbines and PV plants, offer no rotational inertia to the system. This reduced inertia increases the rate of change of frequency (RoCoF) that may trigger frequency relays and causes the automatic under-frequency load shedding. Alternative frequency support methods for low inertia power systems, such as virtual inertia, have been proposed. The virtual inertia

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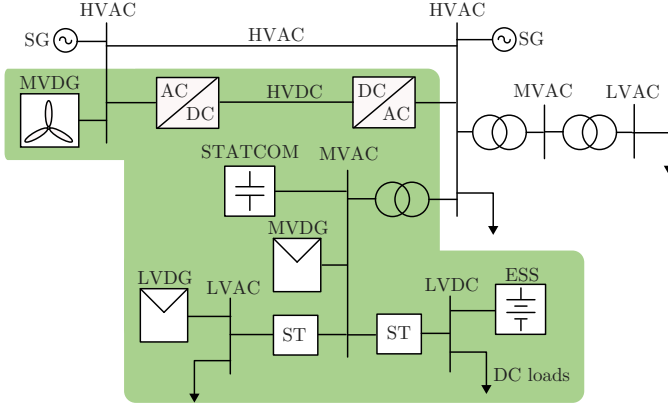


Fig. 1. Power electronics technologies in the electrical grids

is achieved by providing an extra power proportional to the RoCoF. The additional energy can be provided from the rotational inertia of wind turbines, derating the operation of the renewable (PV or wind) generation, or from the energy storage system (ESS) [6].

In transmission systems the power flow is mostly uncontrolled. A “power loop,” which corresponds to power circulating long paths, even several nations, could lead to poor utilization of the transmission grid [7]. One of the most consolidated technology to increase power transmission capability and introduce more controllability in the ac system is the well-known High Voltage dc (HVDC) system [8]. The use of direct current in a hybrid grid scheme and the coordination among energy carriers [9] together with Smart Grid technologies [10], is attempting to give the electrical grid more flexibility in controlling the power flow.

Also, at the distribution level is possible to increase the power capability of the system [11]. For example, it has been demonstrated that the improvement of voltage controllability can unlock up to 3,2 GW of untapped potential [12]. This increment of grid capacity can be done through Smart Transformers which can control the voltage profile, increasing the damping in case of power mismatch [13]. Consequently, the larger damping reduces the Rate of Change of Frequency (ROCOF), allowing the increase of wind penetration up to 20 % [6]. In general, to increase the damping of the system using distributed generation requires a grid forming control scheme [4].

This paper reviews both smart voltage transformation and transmission starting from classifying the adopted operation as grid following and grid forming, since the latter has been emerging in the last years as fundamental contribution to the electric grid stability, then protections in power electronics dominated grid are discussed. In the following the two main technologies, Smart Transformer and HVDC, are reviewed, focusing on their configurations and features but also the challenges these devices and their associated control schemes must withstand. Although only two applications are described, its operation and challenges are common to other applications such as active filters, ESSs and others. Furthermore, STs and HVDC systems are two enablers to energy transition

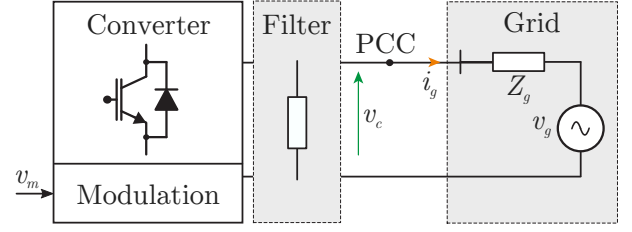


Fig. 2. Grid connected converter.

technology and good examples to illustrate the role of power electronics “system level” solutions into the future power grid.

II. INTEGRATION OF POWER ELECTRONICS CONVERTERS INTO THE ELECTRIC GRID

Distributed Power Generation System (DPGS) based on renewable resources such as wind and solar, as well as STATCOM, ESS, HVDC and ST devices are integrated into the electrical grid through power electronics converters following the configuration shown in Figure 2. The converter is controlled by the modulation voltage and is connected to the point of common coupling (PCC) using a filter.

The control strategy of converters can be configured as either grid-following (GFL) mode or grid forming (GFM) mode, which entitles converters the characteristics of a current source or a voltage source, respectively. A correct operation of GFL converters needs to identify the electric grid impedance and design correctly the PLL, while GFM converters may reinforce the system stability. Main differences of GFM and GFL converters are summarized in following aspects: i) operation principle, ii) response to grid events and iii) synchronization processes [14].

A. Grid Following and Grid Forming Operation

Grid connected power converters are conventionally controlled in GFL mode acting as a controlled current source following the frequency of the reference voltage. Converters with GFL were originally designed to deliver power to the grid by controlling the current, synchronizing its operation with the grid voltage. This control strategy can increase the grid stability by controlling active and reactive power depending on the demand but it does not give support to the grid voltage if this is weak or not existent. The performance of the GFL is usually affected by the grid voltage condition, as well as, interactions with other power converters in the grid can cause voltage and frequency alterations.

Power converters can be otherwise controlled in GFM mode generating a voltage source at its terminals for other converters and loads. The concept of GFM converter was firstly introduced in microgrid applications to enhance system stability and resiliency of power grid with high percentage of power-electronics-based energy generation. Unlike GFL operation mode, the GFM regulates the active or reactive power by directly controlling its voltage at output terminals generating a voltage source. This operation mode can create a voltage in a node were there are no other generators connected

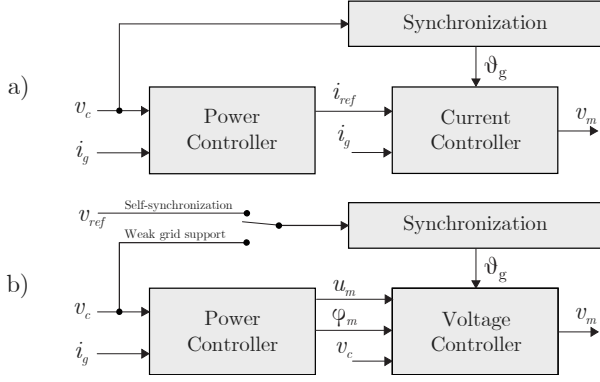


Fig. 3. Simplified control schemes for converters [15]. (a) GFL. (b) GFM.

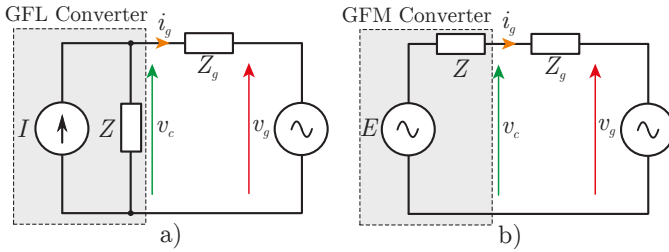


Fig. 4. Simplified representations of converters working with GFL and GFM operating modes: (a) GFL and (b) GFM.

or can provide voltage support when the grid is weak. The last option requires a precise coordination with existing generators. Converters controlled with GFM offer voltage reference for other converters controlled by GFL during grid faults or operation in islanded mode [15].

The simplified control schemes of GFM converter and GFL are shown in Figure 3. Both control schemes have the same objective which is to regulate the active or reactive power by using power controllers. In the GFL operation a current controller is required to manage the current generated by the converter. This controller requires external synchronization with the grid voltage and frequency. The GFM operation requires a voltage control, the reference voltage angle, amplitude and frequency of which can be given flexibly by power controller and synchronization unit in weak grid support or self-synchronization mode. In both modes the output of the control system is the modulating voltage required by the power converter.

A converter working with GFL operating mode can be represented by a controlled current source I in parallel with a high impedance Z , as shown in Fig. 4 a), while a converter working with GFM can be represented by a controlled voltage source E in series with a low impedance Z [16], as shown in Figure 4 b). Both models are interchangeable by Thevenin and Norton equivalents and the actual difference rests on the value of the impedance Z , which in the case of GFM shall be as low as possible to guarantee the voltage source behavior.

B. Response to Grid Faults

The GFM operating mode maintains the voltage phasor E constant in terms of magnitude and phase while GFL applies

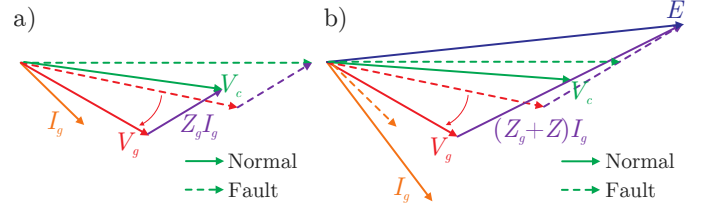


Fig. 5. Phasor diagrams of reactions to grid faults of grid-connected converters: a) GFL and b) GFM.

the same behaviour to grid current i_g . As a result, these two converters performs differently when a grid fault occurs.

The GFL operating mode contributes to a change of converter voltage phasor v_c during the grid fault due to the constant output current phasor. Generally, GFL operation needs a synchronization unit to track the new amplitude and phase of v_c and then calculate the new current setpoint. Therefore, there is a variation of converter voltage phasor v_c during the grid fault as shown in Fig. 5 a). As for GFM operating mode, when the same grid event occurs, it keeps internal converter voltage E unchanged, which is not affected by perturbation of grid voltage v_g . Therefore, converter in GFM operation mode leads to instantaneous variation of current i_g , as shown in Fig. 5 b). Due to the intrinsic behavior of voltage source behind an impedance, GFM converter reacts to the grid event faster than GFL control compensates instantaneous reactive power after grid fault to meet grid codes [17]. A possible control solution to the fault current limiting problem in GFM is given by the virtual impedance [17]. The principle idea is to limit the converter reference voltage according to the variable virtual impedance and thus avoiding the excessive over-current during the low-voltage ride-through action. Nevertheless, the GFM converter still risks of over-current issues when a severe grid fault occurs thus damaging the converter hardware components. In this condition the current is limited only by the input filter hence, a proper design to ensure a current limitation should be provided.

C. Synchronization Approach

The GFL controller needs a synchronization unit which is often implemented by a Phase-Locked-Loop (PLL) [18]. Fig. 6 (a) shows a typical control scheme of synchronous reference frame PLL. As seen in the figure, it identifies the amplitude and phase angle of the grid by sampling the three-phase grid voltages. The amplitude and phase shift of output current can be calculated according to the defined active power and reactive power.

Although the PLL shows good performance in identifying grid voltages, it can generate stability issues to the converter under weak grid condition, which could be overcome at cost of control bandwidth of PLL. Conversely, the decrease of the control bandwidth leads to poor dynamics of acquiring grid voltage angle which cannot satisfy the requirement of quick reactions to grid faults [19]. The bandwidth of PLL will be limited when the converter operates at low short-circuit-ratio (SCR) grid and there are other PLL-based converters nearby.

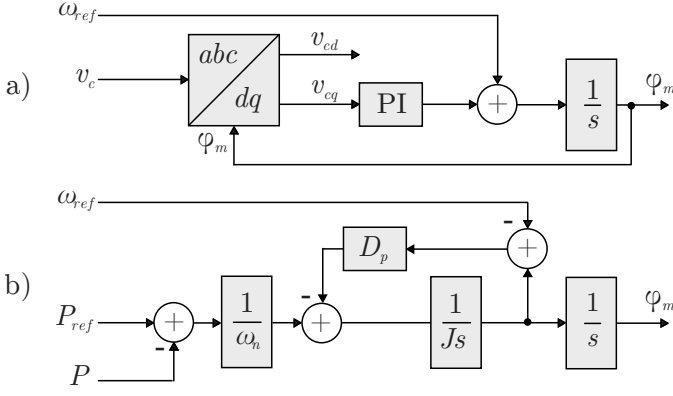


Fig. 6. Control scheme of converter synchronization: a) SRF-PLL and b) synchronverter.

Moreover, the interaction between these PLL-based converters becomes stronger with the decrease of SCR [19].

As for GFM converter, it can be self-synchronized to the grid by power control approached which emulates the power synchronization principles of a real synchronous generator (SG), such as power synchronization control [20], droop control [21] and synchronverter control [22]. Synchronization based on synchronverter approach has become more popular because it doesn't require a different unit for pre-synchronization and normal operation. The control scheme of synchronization control is shown in Fig. 6 b). Results indicate that the synchronverter-based GFM converter operating nearby helps to enhance robust stability of the PLL-based converter [23] under weak grid condition. therefore, GFM converters are much more suitable for weak grid condition compared to GFL converters. However, GFM converters are more likely to behave instably under stiff grid condition [24].

With the increasing penetration of renewable energy and distributed energy resources (DERs), the inertia offered by SGs to the system is decreased, which leads to frequency stability issues [25]. Operators in South Australia are already facing obstacles regarding the high penetration of inverter-based sources during certain periods of the day [26]. Due to different output characteristics of GFL converter and GFM converter, their response to frequency variation would be different. For a mixed system which includes SGs, GFM converters and GFL converters, the increase share of GFM converters helps to provide more damping to frequency swing while GFL converters generates the opposite effect with the increase of its share [4]. Therefore, reserves of GFM converters in a low-inertia system has the potential to greatly reduce frequency swings as well as reduce rate of change of frequency (ROCOF), allowing a larger percentage of power converters integrated to the grid.

D. Challenges for Grid Forming Operation

Although GFM control has better frequency response than GFL and enhances system stability, there are still many challenges needed to be addressed.

- a) Synchronization stability: It's of great significance for a converter to keep synchronization with the grid. In GFM mode the current injected to the grid can be derived by

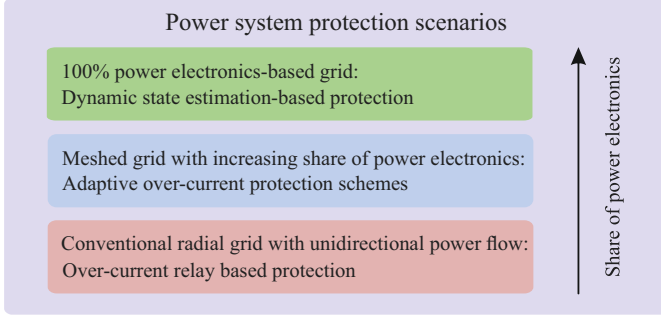
the power angle relationship between the grid voltage and the equivalent output voltage of the converter. Under stiff grid condition, even a small disturbance of grid voltage can lead to an instantaneous change of current, causing large power variations. Therefore, control method with much more damping and robustness against large variation of SCR are required [27].

- b) Synchronization during faults: During severe grid faults the transient stability of GFM control with power synchronization and synthetic inertia exhibits a second-order nonlinear dynamics behavior, which is similar to the power-swing dynamics of SGs [28]. The fault current is generally controlled by the PLL, which also performs similar dynamics as the power-swing dynamics of SGs potentially triggering the over-current protection during the transient [29]. Therefore, a PLL approach to perform faster dynamics during severe grid faults should be investigated.
- c) Current limitation and fault-ride through (FRT): Under grid faults, over-currents may damage the hardware of the converter or may trigger over-current protection. Therefore, proper strategies to deal with over-currents, as well as, ride through strategies should be implemented [30].
- d) Transition between islanded and grid-connected modes: The converter may be disconnected from the grid during fault, which may causes significant deviations and oscillations due to the undesired mismatch of frequency, voltage or non-zero through-power. Therefore, strategies that can be applied in the grid-connected mode and the islanded mode are required ensuring seamless-transitions between both operating modes [31].

E. Power system protection with increasing power electronic converter integration

The conventional power system protection is based on current sensing devices, such as over-current relays, reclosers and fuses [32]. These devices monitor the fault current flow and generate trip signals to the circuit breaker in case the fault current exceeds a pre-defined threshold. However, this approach is based on the assumption of radial feeders and unidirectional power flow, which isn't necessarily true with the increasing penetration of power electronics based RES [33]. Moreover, the RES change the fault level (as they contribute only with small portion to the fault currents) and have variable power in-feed by nature. In consequence, the conventional power system protection experiences a number of challenges [32]: 1) Blinding of protection, i.e. upstream relays will sense lower fault currents if the downstream integrated RES share increases, 2) False or sympathetic tripping, i.e. due to the bidirectional fault current flow a relay in a healthy feeder may trip on the backward fault current, 3) Islanding problems in microgrids [33], in which the fault current magnitude and direction changes from grid-connected to islanded mode and 4) Loss of coordination, i.e. a sequential false operation of relays, which may also impact the distance relays of the transmission systems, in which false tripping due to under- or over-reach issues of the protection zone may result. Consequently, faults within the protection region may be overseen (under-reach)

TABLE I
POWER SYSTEM PROTECTION SCENARIOS.



and false tripping on external faults (over-reach) may happen. As indicated in Table I in the intermediate meshed grid scenario, novel protection schemes are necessary, which can be classified in adaptive and non-adaptive strategies [32]. In the adaptive protection, the relay settings are changed with respect to the changing fault level in the power system to ensure a reliable distinction between normal loading and fault condition. This requires the interconnection of relays, switching devices and control centers with reliable bi-directional communication infrastructure. Alternatively, additional devices can be installed to minimize or block the RES fault current contribution (non-adaptive strategy). Directional over-current relays can be employed to avoid sympathetic tripping. In a close to 100% power electronics based grid, a generalization of the differential protection approach, the so-called dynamic state estimation based protection can be seen as a viable protection solution without any a priori protection relay settings [34]–[36]. Enabled by the wide-spread existence of phasor measurement units (PMU) and advanced communication infrastructure, multiple measurements (e.g. currents and voltages at the terminals as well as inside the protection zone and thermal parameters) are captured to create a model of the dynamics of power system states. Testing the consistency between the real-time PMU measurements and the dynamical model of the protection zone a reliable fault sensing can be guaranteed. The confidence level, i.e. the fit between the measurements and dynamic model, results to be close to one in normal operation or external fault condition and drops to almost zero during internal faults, which in turn initiates the trip signal to the circuit breaker. The benefits of the dynamic state estimation based protection are simplified protection settings without coordination with other protection functions, its immunity to current inversion and the capability to detect high-impedance faults dependably and securely.

III. SMART TRANSFORMER

The Smart Transformer (ST) is a power electronics-based transformer with advanced control functionalities to allow flexible AC and DC distribution and the possibility to provide grid services [13]. Thus, it is not a one-by-one replacement of the conventional transformer [37] with the limited functionality to step up/down the voltage between primary and secondary side, but instead forms an active and smart node to allow

high penetration of distributed renewable energy, integration of storage in the electric distribution grid and electrification of transport and heating [38].

The ST is also known as energy router [39] or energy hub, which describes its main responsibility in the power system: To manage the transmission and distribution of energy (similar to an information network) and allow for dynamic adjustments of energy flow [40] and real-time communication among grid elements [41]. As explained with more details in the following sections, the ST can measure grid variables, observe the grid status and perform optimization and complex control tasks.

In the demonstrator project LV-Engine [42] a fit-for-purpose ST is intended to be implemented in the secondary substation of the Scottish distribution grid with the aim to enhance the flexibility and release more capacity for the connection of low carbon technologies. The project LV-Engine establishes five main use cases of the ST in the near future, which are optimum real time phase voltage regulation through GFM mode, a meshed LV network operation, the provision of LVDC supply for electric vehicles charging, phase balancing and power capacity sharing between secondary substations.

The replacement of conventional transformers by their smart counterpart has to be understood as a process. However, already smaller share of ST in the grid brings improvements in terms of released capacity in existing LV network for connection of future RES generation and load prior to costly grid reinforcements, the increased flexibility and adaptability to cope with uncertainties in how energy will be generated and consumed and lastly the expected avoidance of losses through more efficient DC based integration of EV charging. Thus, the project LV-Engine expects financial savings of 62 million £ by 2030 and 528 million £ by 2050 with only 16% of GBs 11 kV / LV transformers being substituted by 2050.

Another recent utilization of the ST can be found in the German initiative ENSURE [43], in which field trials of the ST in a hybrid AC/DC grid infrastructure at distribution grid level are carried out with the aim to efficiently integrate EV charging infrastructure and PV systems.

A. Smart Transformer Control in Hybrid and Meshed Grids

The classical configuration of the distribution grid is a radial ac grid. However, the increasing share of RES and the need to efficiently integrate storage or EV charging stations calls for hybrid and meshed distribution grids, which combine dc and ac grids and allow more flexible power flow as each grid node is at least supplied from two sides [44]. The ST, even when operated in parallel with conventional transformers [45], can be seen as an enabler of such grid scenario as it provides dc connectivity [46] and allows to route the energy flow, i.e., in contrast to conventional secondary substation transformers, can control the active and reactive power exchange with the connected grids [40].

The control of the ST can be divided in three main control layers [40], which are shown in Tab. II. The inner control layer is the current or voltage control layer including also the modulation. At this level the balancing of dc-link voltages, power balancing in the dc/dc isolation stage and the closed-loop

TABLE II
OVERVIEW OF ST CONTROL.

Smart Transformer Control Overview	
Third control layer	<ul style="list-style-type: none"> • Generation of set-points for active and reactive power demand • System level commutation • Power grid monitoring
Second control layer	<ul style="list-style-type: none"> • Generation of set-points for first control layer • Power flow and quality management • Dynamic grid voltage control • Dc and ac microgrid integration
First control layer	<ul style="list-style-type: none"> • Dc-link voltage balancing • Power balancing of isolated converters • Grid-forming/following control • Modulation • Fault-reconfiguration and protections

voltage or current control are performed. The second control layer is responsible for the provision of set-points to the inner control layer. It involves grid services, power flow control, dynamic grid voltage control (e.g., low-voltage ride through) and possible dc microgrid control for the integration of storage and distributed energy resources. In the outer control layer, set-points for active and reactive power are defined coordinating multiple STs and other grid assets such as DG and loads, and allocate their respective power flows. It involves system level communication among several STs and grid monitoring. As an example, in a ST-fed variable frequency distribution grid, in which due to the asynchronous interconnection the LV grid frequency can be chosen independently of the MV grid frequency, the ST can interact with the local generators and load characteristics to control the LV power demand [47].

The meshed grid operation allows more flexible control scheme of the ST as the grid voltage can be established already by the parallel conventional power transformer. Thus, the LV inverter can be controlled in GFL to achieve a more flexible power control to provide supports in the LV ac grid and high current quality. The integration of ESS in the dc link increases the dc voltage control flexibility, i.e., either achieving independent operation of ST and MV ac grid support or allowing for so-called dual microgrid operation, if the ESS is controlling the LV dc voltage.

The ST enables meshed grid configurations as shown in 7. Connecting two parallel LV ac feeders at the busbar is possible to achieve equal power demand distribution, i.e., to balance feeders with high load and high distributed generation (DG) in-feed. Consequently, the appliances overload condition and feeder voltage profile can be improved. By re-configuring the network in a ring topology closing the loop at the end of the feeder through the normal open point similar benefits can be obtained.

In the case of a upstream power transformer outage or maintenance, the ST can establish a microgrid in both the LV and MVac side by switching the control operation of both MV and LV converter into GFM. This dual microgrid operation allows - assuming the presence of sufficiently large

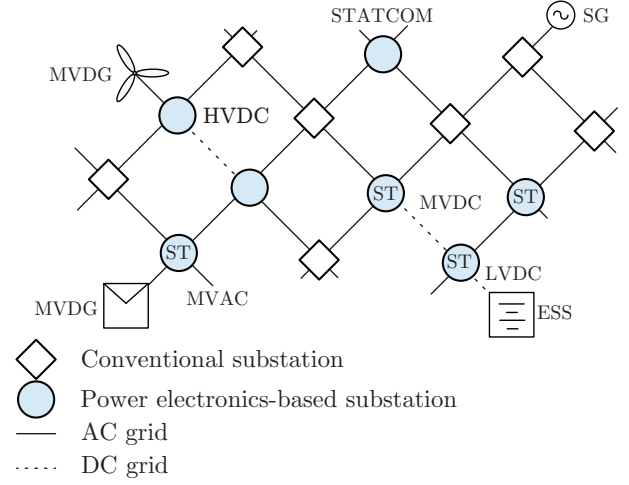


Fig. 7. ST in meshed grids

battery energy storage systems (BESS) as primary power source - continuous power supply of the loads with control of voltage and frequency in both grids [48]. Closing the normally open point to establish the ring grid configuration, the dual microgrid can be achieved with reduced line losses as compared to the radial grid configuration and the voltage along the feeder can be maintained within the specified grid code limits [44].

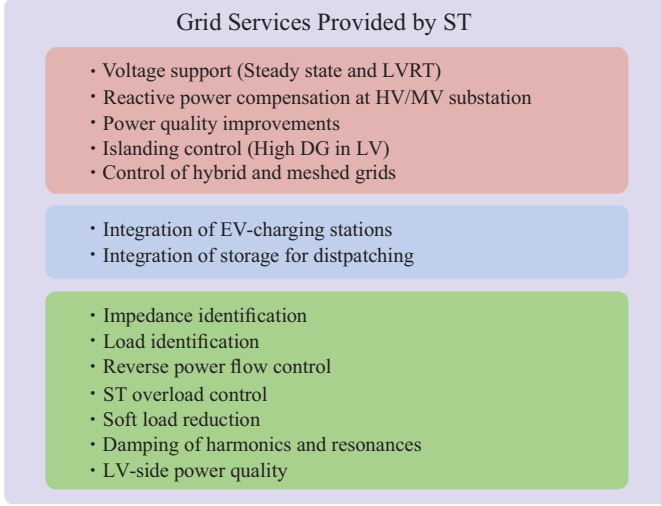
In the multi-port topology, the ST provides direct dc connections in low and medium voltage. This allows the direct and efficient integration of e.g., BESS [49] and ST-connected RES with reduced operating losses, reducing the number of power conversion stages and keeping the grid infrastructure light [49], and the possibility to offer harmonic compensation and improved power quality [45]. The ST enables hybrid microgrids, i.e., ac and dc microgrids, which can be operated in zones of local energy balance by either centralized [50] or decentralized [51] power management schemes and the ST only provides the backup power in case the local DG and storage can no longer maintain the power balance.

A future scenario the LV dc port of the ST is extended to establish an extra dc line to connect with the dc bus of distributed generation converters and dc loads. Bringing the DG active power supply and loads closer together and draining power from the ST only in case the DGs are insufficient to supply the loads, increases further the efficiency or in case of reverse power flow and allows a reduction of the ST LV ac/dc converter [52]. A novel interconnected topology of the multiport ST has been presented in [53], which considers optimal power routing by design based on the power demand in the LV dc and LV ac grids.

Interconnecting two STs in distinct MV feeders through an additional MV dc line achieves higher grid resilience towards faults and supply redundancy [54]. The ST itself can also increase the grid resilience by riding through single-phase faults in the downstream grid controlling the phase angle as proposed in [55].

The ST with integrated storage can also provide a dispatched-by-design operation of the LV distribution grid

TABLE III
CLASSIFICATION OF ST GRID SERVICES.



[56], while ensuring improved voltage control performance in LV and MV network with respect to the base case of conventional power transformer and separate LV storage unit.

Another future scenario facilitated by the ST is a multi-frequency distribution grid, in which point-to-point energy transfer from a particular sender to a particular receiver is enabled by the ST's potential to modulate more than one single frequency in its output voltage waveform [57].

B. Smart Transformer Grid Services

What makes the ST *smart* are the advanced control functionalities and the distribution grid services that are enabled thereof [58]. In Table III, a classification of the potential services that a three-stage ST can provide to the MV ac and LV ac grid, as well as, the advantages that are facilitated by the dc connectivity is given.

A strategy using the ST to identify the load dependence on the grid voltage in real-time by means of intentional small voltage perturbations and capturing the respective load power response has been proposed [59]. The knowledge on load sensitivity allows a proper and smooth control action, for instance, voltage control for stability purposes or voltage and frequency regulation, under an increased demand variability and different loading conditions in the power grid.

A soft load reduction control to avoid load shedding has been developed, which enables the ST to decrease the consumed load active power by controlling the voltage in the LV grid according to the identified load sensitivity [60]. Likewise, the ST can guarantee a pre-specified load flexibility to the transmission or distribution system operator and maintain its own operational safety by means of overload control. Moreover, the load control can be applied to improve the voltage profile in the MV grid prior to the action of on-load tap changers [61].

The reduction of the grid equivalent inertia due to the increasing number of PE-connected DG units requests a

frequency regulation with high dynamics. The ST can provide such service by controlling the load consumption as power reserve, both upward and downward, during frequency variations [62]. A study case in the Irish transmission grid system with wide-spread use of ST has been investigated, introducing a flexible demand control to support the frequency and simultaneously the voltage by reactive power control with the aim to increase the grid's hosting capacity for renewable energy systems. A 10 % increase in wind penetration without any additional storage units has been achieved [6].

As countermeasure towards the reverse power flow from the LV to MV side of the distribution grid in the case of high DG power generation and low load demand, the ST can modify the voltage waveform by varying the frequency in the LV grid in order to interact with the local DG units, which in turn will vary their power output avoiding the reverse power flow and possible voltage rise in the MV side [63].

The ST can be exploited to enhance the possibility of islanding operation in multi-microgrids. Multi-microgrids are defined as MV grid interconnecting several aggregated LV microgrids aiming to increase the distribution grid resilience. In [64] robust control strategies for ST with and without integrated storage units have been presented, which aim to coordinate the flexibility of distributed resources in LV and MV grid as well as the optional storage unit in order to guarantee a successful multi-microgrid operation in islanded mode. The ST can be controlled such that the LV microgrid frequency is modulated following the MV grid frequency, which allows the participation of LV DGs in the MV primary frequency regulation. Furthermore, the storage unit integrated in the ST LV dc link enables the restoration of the LV MG frequency, once the MV frequency is resettled within the dead-band limits.

The control concepts established for the islanding operation can be extended to a local black start operation in case of upstream voltage level blackout or fault in the HV grid. The ST LV inverter will transit to GFM and especially if equipped with ESS will be able to initiate a soft-start [65] preventing the ST from high inrush currents and maintaining balanced MV dc-link voltages [66] and create references for the frequency and voltage in the multi-microgrid with the aim to recover pre-fault conditions of load and generation levels and finally to allow the re-synchronization to the upstream grid [67].

Forming a non-synchronous interconnection between the LV and MV ac grids, the ST decouples the two and hence prevents harmonic propagation from one side to the other. In addition, the advanced control functionalities allow further improvement of grid power quality in terms of harmonics and resonances. As demonstrated in [68], the ST can effectively reduce the unbalance degree in the MV grid and considerably improve the current quality in MV and voltage quality in LV grid. The ST can actively identify grid resonances by mono-frequency excitation to allow resonance adaptivity of the grid forming control strategy to LV grid variations [69]. Moreover, the ST can be seamlessly equipped with filter-based or multi-loop-based active damping controller to shape its output impedance, damp possible grid resonances and increase the grid stability and the stability of the local DG controllers [70].

The flexibility reached with the implementation of services reported in Table II demands important hardware or software modifications into the traditional ST architecture. This additional complexity is directly traduced in terms of cost for the ST unit. As solution, in [58], the grid-tailored design approach has been proposed, which considers the apparent power controllability of the ST to achieve up to 20% reduction in terms of costs and footprint with respect to the conventional transformer design approach. In fact, depending on the requested grid service functionality savings achieved in one stage of the ST can compensate the additional costs of other stages. In the design approach semiconductor, cooling system and capacitor bank design have been considered. The conventional strategy to prove benefits of grid services in term of cost is the utilization of Real-Time simulation-based testing of STs under different grid services, faults and load requirements [71].

C. Smart Transformer Maintenance-oriented Control

Reliability and maintenance costs are still key concerns for the ST [72], in which an industry survey identified the thermal stress of power semiconductors and capacitors as the main source of failure [73].

As demonstrated in the European Research Council (ERC) Consolidator Grant HEART (Highly Efficient And Reliable smart Transformer) and the following ERC Proof of Concept Grant U-HEART (Unbreakable- Highly Efficient and Reliable smart Transformer) modularity in the design, i.e., serial or parallel connection of basic power electronic building blocks, creates inherent fault tolerant capability and self-healing features to increase the STs robustness and reliability [72].

A software-based approach to reduce the thermal stress on the STs components is given by the active thermal control [74]. Due to the activation and deactivation of PEBBs to increase the STs efficiency, different components are exposed to different failure mechanisms and stress. However, to increase the system reliability and avoid or delay as much as possible the failures dependent on the processed power, the PEBBs can be unequally loaded (which is referred to as "Power Routing") to shift the stress from older to newer components [74] considering the estimation of the junction temperature on the basis of thermo-sensitive electrical parameters [75], and the remaining useful lifetime. Likewise, lower safety margins and thus a lighter infrastructure can be realized [72].

The active thermal control (ATC) concept can be implemented at different layers [75] ranging from modulation, changing the switching frequency or modulation type [76], [77], to converter or system level control, where the dc-link voltage control can be adapted or the active/ reactive power profiles can be reshaped introducing virtual resistors to mirror the aging of the individual PEBBs [78]. This power routing concept is applied to increase the remaining useful lifetime, reduce the maintenance costs and increase the availability of power supply and grid services through prognostic maintenance [79].

D. Remaining Challenges

In the recent decade, several implementation issues of STs have been sorted. However, there are still some technological and economic challenges to overcome before SSTs fully replace conventional transformers [40]. These challenges are summarized below.

STs are still more expensive than traditional transformers. However, semiconductor technology is continuously improving, developing new efficient and cheaper high voltage/current semiconductor devices. Modular design enables self-healing features, i.e., the correct fault operation bypassing damaged powers cells. In fact, a modular design allows reduce the power outting and balance the aging cell effects, thus failure rate is reduced and their lifetime is improved. Furthermore, a ST configuration requires an high-frequency isolation transformer, then the incorporation of fast semiconductor devices can be potentially good for ST operation [80]. In this sense, the utilization of new highly efficient components, such as fast high-voltage Si-IGBTs, SiC-MOSFETs and GaN-HEMTs will open new research lines. One of the major benefits attained from the utilization of wide bandgap devices arises from their ability to operate at high switching frequencies while still maintaining a high efficiency. Moreover, the increase of the breakdown voltage, enabled by the development of HV SiC devices, translates into the utilization of fewer devices in a topology. The collection of these two aspects contribute to a reduced footprint, system losses (once the technology is matured) and CO₂ emissions. Although extremely beneficial, the challenges attached to their full utilization still need to be completely addressed. From the series arrangement of the SiC dies and challenges in managing the high dv/dt [81] to the requirements for appropriate packages, able to ensure the high voltage insulation and good thermal performance, these devices have not yet found a mass scale opportunity to bring down their prices and make them competitive with Si-based solutions [82].

Other relevant operation challenges such as increased over-current and overvoltage capabilities during grid faults, fault detection and precise synchronization methods based on spread communication lines and real-time security algorithms must be adopted and solved in order to increase the robustness of ST substations. Finally, there are still several challenges to increase the utilization of STs into the power grid. Developing of new standards and grid codes oriented to define the interaction between STs and the power grid is a mandatory task in order to make ST an industrial product [40].

IV. HVDC SYSTEMS

HVDC have proved to be cost efficient alternative to ac transmission for long distance energy transmission due to the lower cost of lines and reduced same right-of-way (RoW) [83]. Urban areas infeed and off-shore wind farms using underground or submarine cable also benefits from this technology [84]. The interconnection of asynchronous grids, even with different frequencies, can also take advantage of this technology using back-to-back systems in which there is no transmission line involved [85]. The fast dynamical

response, improved stability and distributed control capability of HVDC might be the key to increase renewable energies utilization [86]. Moreover, HVDC can be embedded in the legacy AC power system [87]. Increasing the interconnectivity, the embedded HVDC has the potential to reinforce the hosting capacity of the AC grid by providing control services and thus reducing the investment needed in terms of conventional grid infrastructure upgrades.

HVDC technology is rather mature, but as the number of HVDC in worldwide power systems is increasing new challenges have been emerged. Reduction of interarea sub-synchronous oscillations, fast frequency regulation, weak grid operation and protection strategies for increasing reliability are some of them. In this section a review of HVDC technologies and recent advances on the topics mentioned previously are discussed.

A. HVDC Technologies

Thyristor based HVDC technology was introduced in the 1970 decade proving to be lighter, cheaper, more reliable and more efficient than the previous technology based on mercury valves [88]. This HVDC technology uses line commutated converters (LCC) which are composed by an arrangement of six switches, each one made of several semiconductors connected in series to achieve the transmission DC voltage range. To control the DC voltage and hence the active power, the firing angle is modified and, intrinsically, there is a coupled relationship between active and reactive power. These converters requires reactive power and cannot be connected to passive grids which do not have voltage sources in the AC side or weak grids where the reactive power could not be properly controlled.

The six pulse rectifier generates characteristic harmonics in the ac current and in the dc voltage requiring large filters in both sides. It is possible to connect several six-pulse rectifiers using a transformer with phase-shifted secondaries generating a multipulse input current (12/24/36 pulses). In Fig. 8 a) is depicted a 12-pulse LCC-based HVDC system. This configuration reduces the harmonics in the DC voltage and AC current but also reduces the overall efficiency due to the transformer [89]. The reactive power requirements of LCC-based HVDC can be reduced by using Capacitor Commutated Converters (CCC) as is presented in Fig. 8 b).

Voltage source converters (VSC) with force commutated semiconductors (IGBT) were introduced in HVDC systems employing modular multilevel converter (MMC). The main advantage of this topology is that the generated voltage is composed by several small voltage steps, hence important improvements are obtained as such as minimization of harmonic generation, elimination of the input filter, low HF noise, low switching losses, low semiconductor switching frequency, and nearly sinusoidal AC voltage waveforms. These converters do not require any reactive power compensation, and moreover they can control independently both active and reactive power with high dynamic, hence these converters can be connected to weak networks and even to passive networks without synchronous generators in it. However, compared to

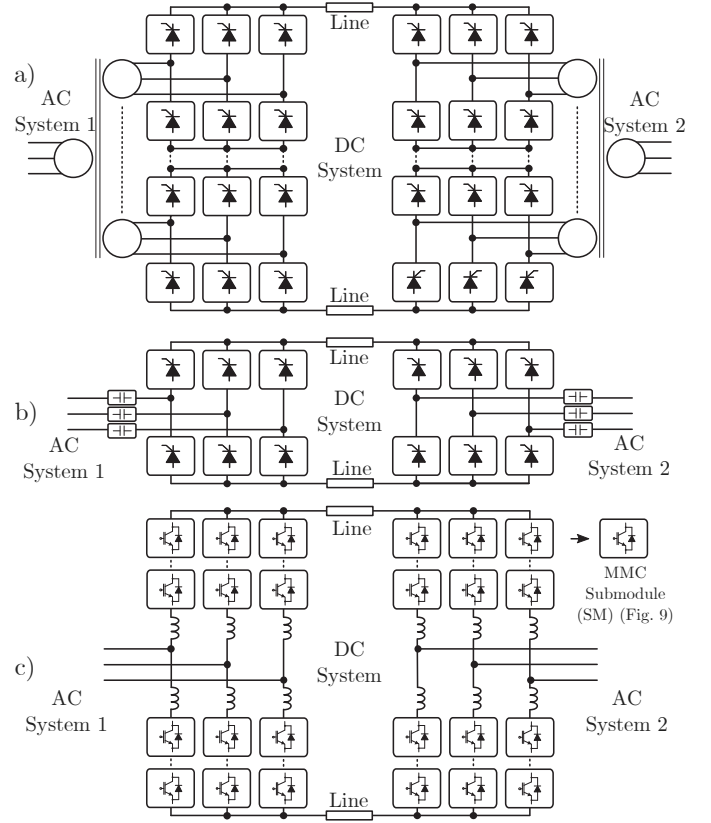


Fig. 8. HVDC Technologies: a) LCC, b) CCC and c) MMC

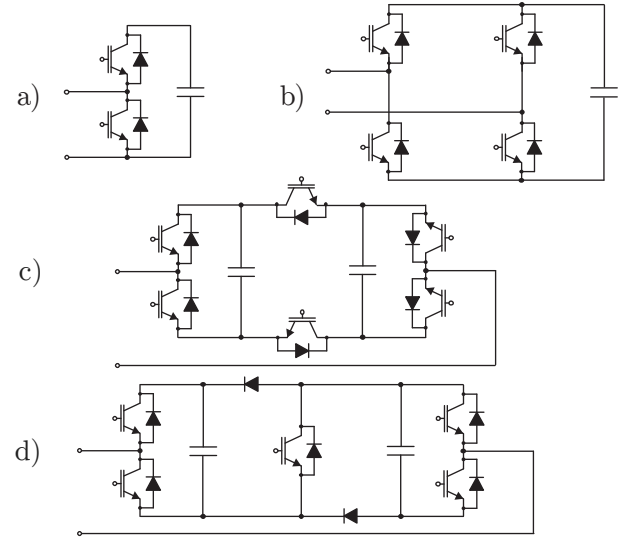


Fig. 9. MMC submodules: a) half-bridge submodule (HBSM), b) full-bridge submodule (FBSM), c) cross-connected submodule (CCSM) and clamped-double submodule (CDSM).

LCC-based HVDC the DC voltage and power transmission capability is lower [90]. A conventional MMC-based HVDC system is presented in Fig. 8 c).

This technology is based on the series connection of several voltage source simple submodules as shown in Fig. 9. The half-bridge submodule (HBSM) shown in Fig. 9 a) provides low switching count but it generates only zero and posi-

tive voltages. Other possibility is the full-bridge submodule (FBSM) depicted in Fig. 9 b). It generates zero, positive and negative voltages, then this type of cells can be used either for ac or dc systems. On the other hand, advanced bipolar submodules such as the cross-connected submodule (CCSM) in Fig. 9 c) and the clamped double submodule (CDSM) in 9 d) can be used o provide fault blocking capabilities.

LCC-based and VSC-based HVDC technologies offer advantages and the same time some technical drawbacks. LCC-based HVDC systems needs large amounts of reactive power to deliver active power and large filters for the high harmonic content. On the other hand, VSC-based systems provide independent control of active and reactive power in addition to easier reversal power flow capability. Furthermore, VSC-based HVDC systems are less efficient than LCC-based HVSC and have much higher cost due to large number of semiconductors [91]. The combination of both units can be a potential solution, combining the advantages of LCC-based and VSC-based HVDC technologies. However, with the continuous technology improvement of semiconductor devices such as high-speed IGBTs and power MOSFETs a massive utilization of MMC-based units in new HVDC projects is expected.

Fast semiconductor devices as SiC-MOSFETs have been evaluated for use in MMC cells and it was found that they could further reduce the losses, improving the efficiency and increasing the power density [92], [93] to the detriment of a high cost. Finally, a potential use of fast high-voltage Si-IGBTs and SiC-MOSFETs in MMC-based HVDC systems is in the protection bypass, breaker circuits and in dc-MMC units for direct photovoltaic energy integration [94].

B. HVDC Control Strategies

There are different control strategies depending on the control objectives. At system level, different control strategies are required to interface the HVDC system with the ac grid such as voltage margin control, droop control, voltage and frequency regulation, synthetic inertia and grid forming. These strategies, however, are common to all devices connected in a grid. This section is focused on control strategies required specifically for HVDC system.

The controllers needed in an HVDC system are classified by four functional levels according with the International Council on Large Electric Systems (CIGRE) guide [95], shown in Fig. 10: station-, upper-, lower- and hardware-level controls. The station controls provide the set-points for active power (P), DC voltage (VDC), reactive power (Q) or AC voltage (VAC) required by the next control level. Upper-level control address the HVDC mode operation which depends on the HVDC configuration (back-to-back, point-to-point, multi-terminal) but is independent of the converter topology. The upper level control presents two main control operation modes: grid-following and grid-forming control modes. In the grid-following mode, the unit can be connected to a non-islanded AC system, where active and reactive power control or DC-link voltage control and AC-grid voltage control can be achieved. Both alternatives have an internal decoupled current control and the lower level reference generation is synchronous with the grid voltage by

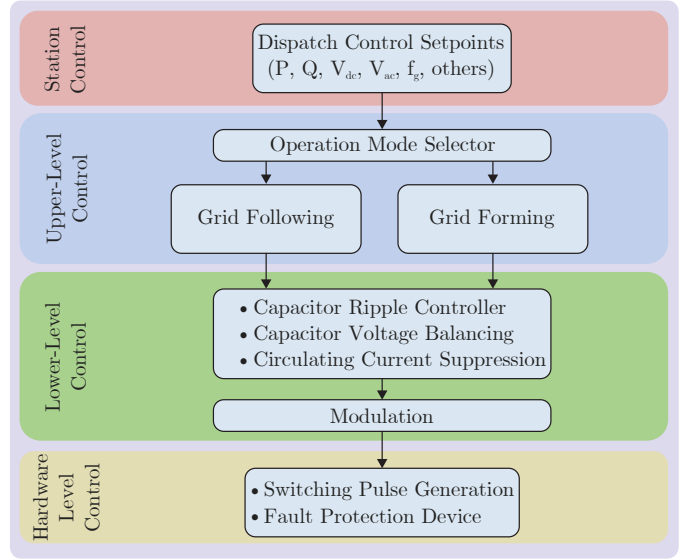


Fig. 10. Hierarchy Control Structure of HVDC-VSC MMC Systems.

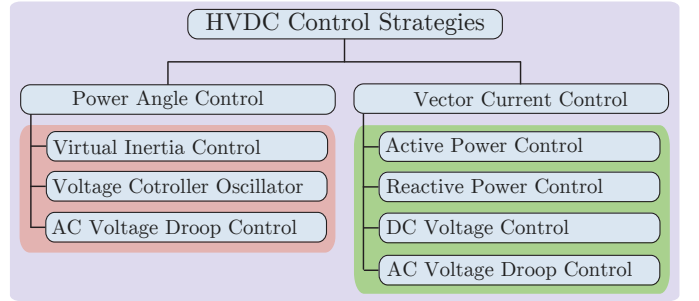


Fig. 11. Classification of control strategies for HVDC

using a Reference-Frame-Phase-Locked-Loop (SRF-PLL) or Double Decoupled SRF-PLL in case of unbalanced AC system connection. On the other hand, if the grid-forming control mode is selected, the unit can be connected to an islanded AC system, and the grid voltage must be synthesized by the converter unit. The HVDC control strategies are summarized in Fig. 11.

Lower-level controls address the modulation and dedicated control constrains for the converter operation hence they must be designed specifically for LCC or MMC converters. Due to the large number of voltage levels in MMC-based HVDC units, the Staircase or Nearest-Level Modulation (NLM) provides a simple implementation and calculation of gating signals. A combination of NLM and PWM, in which only one submodule per arm is modulated, can reduce the low-frequency current distortion generated by NLM without increasing the modulation complexity [96]. On the other hand, in industrial applications, high-frequency PWM is not used to avoid increasing commutation losses and optimal-pulse pattern generation is preferred [97]. If PWM is required, a carrier equal to the fundamental power-line (50Hz or 60Hz) as switching frequency per semiconductor device can be adopted.

V. CHALLENGES TO INTEGRATE HVDC INTO ELECTRICAL GRIDS

New power converter technologies based on voltage source converters have pushed the use of HVDC on new applications resulting in a wide variety of challenges which must be addressed during the next years. Most of these challenges are summarized in Table IV and they are related to the growth of renewable energy sources integrated to the electrical system in order to increase efficiency, stability and reliability. In this section several of these challenges are described.

A. Sub Synchronous Interarea oscillations

The interaction of the HVDC controllers and the mechanical time constant of the ac machines can lead to low frequency oscillations also called as sub synchronous resonances (SSR). These resonances might lead to large voltage and currents excursions damaging the system components and activating the protection devices. Even when these resonances are limited in amplitude, if they are generated continuously, torsional oscillations can lead to the fatigue and eventual failure of the rotating machines.

The LCC-HVDC can generate SSR if the equivalent impedance generate by the rectifier station has a strong modal resonance. The solution proposed to reduce these oscillations is modifying the tuning of the controller parameters in order to generate active damping [98].

This effect is less likely to occur in VSC-HVDC because the dynamics of the controllers are faster than LCC-HVDC. However, it has been demonstrated, using modal frequency linear analysis, that this effect can be still produced, particularly if the HVDC station is implemented with constant power control. In this condition the impedance is reduced and there exists a small damping to avoid oscillations [99].

Interarea SSR can be also generated by the primary control implemented in the HVDC station for frequency regulation. This type of interaction between the primary control and mechanical elements of the grid can lead to very slow SSR in the order of 0.1-0.7Hz and, which can be avoided, or at least reduced, by a proper design of the controller [100].

Although the main cause of SSR is the interaction of the controller with mechanical devices, for long lines it can also be produced in the HVDC line by an oscillating power exchange between stations. The DC filters increase the resonance peak and, in this case, it is possible to reduce it by limiting the gain of the controller for subsynchronous frequencies [101].

Another cause of SSR is in multiterminal HVDC due to the master-slave configuration in which there is only one station controlling the DC voltage and all the other stations are controlling power. In these cases the most commonly proposed solution is to model a resistor in series with the DC line into the control system in order to produce virtual damping [102].

The main challenge to reduce SSR is the requirement to perform a modal analysis of the system in order to model the coupling between the HVDC and ac systems and identify the cause of the oscillation. This task is not trivial and required a detailed knowledge of the parameters of lines and generators, as well as, the different configurations of the grid [103].

TABLE IV
CHALLENGES TO INTEGRATE HVDC INTO ELECTRICAL GRIDS.

HVDC Challenges	
Subsynchronous resonances	<ul style="list-style-type: none"> • Frequency and voltage resonance • Power modulation • Online identification of oscillations
Fast frequency regulation	<ul style="list-style-type: none"> • Incorporation of energy storage • Fast control of DC voltage • Multiterminal HVDC
Weak grid operation	<ul style="list-style-type: none"> • VSC-HVDC voltage support • Grid forming strategies
Faults and protections	<ul style="list-style-type: none"> • Resonant circuits for breakers • Inherent VSC-HVDC fault capability • AC and DC fault tolerant operation • Ultrafast fault detection and location

One possible solution is to apply an active power modulation in which the power of each HVDC station is linked to the frequency variation similarly to droop control [104]. If the dynamics of the source are neglected this method is only limited by the available power, but if these dynamics are considered there exists a fundamental limit to the performance given by the ratio between modal frequencies [105].

The flexibility achieved with the implementation of challenges reported in Table IV demands important modifications into the conventional control schemes summarized in Fig. 11. On the other hand, if conventional control schemes are retained without modifications, undesired loop energy flow may appears by increasing the converter losses and complexity of HVDC protection systems [106].

B. Fast frequency regulation

Large-scale integration of renewable energy has increasingly reduced the inertia of power systems because this kind of energy sources does not provide any inertia in the case of photo-voltaic solar energy and only a very little mechanical inertia in the case of wind power. The reduction of the system inertia might lead to larger and faster frequency deviations which can activate protection systems and reduce their stability. Note that, the implementation of the synthetic inertia concept in power systems with high penetration of renewable energy sources is performed with a derated maximum power-point tracking (MPPT) operation also named flexible MPP and energy storage source installations.

In this scenario, VSC-HVDC, due to the fast dynamical response of currents, can be used to alleviate this problem by incorporating synthetic inertia and damping into the system. The control system of the HVDC must be modified to mimic the behavior of a synchronous machine in which the frequency is related to the power extracted or injected, hence from the point of view of the grid, and the HVDC station becomes a large synchronous machine with synthetic mechanical inertia associated.

Similar to a mechanical system, the slow rate of change of frequency provided by the inertia consumes or adds kinetic

energy from the rotating machine. With synthetic inertia, the energy comes from the DC terminals of the HVDC station, which doesn't inherently have an energy storage system to cope with the energy. Several methods to provide this energy from the DC-link have been proposed, such as increasing the DC capacitance by installing distributed capacitors along the DC line [107]. The DC voltage can also be modified to provide this energy, but in HVDC systems, there are strict limitations regarding DC voltage due to isolation and operation issues [108].

In a multi-terminal HVDC configuration with a master-slave control scheme, the energy required to provide synthetic inertia can be easily obtained from the master station as well as the AC system is large enough to be considered as an infinite system [109]. Distributed battery energy storage connected to each submodule of the HVDC station can provide the required energy to implement synthetic inertia. The main challenge of this alternative is the internal current and energy control to keep the batteries charged without compromise the control of AC and DC currents [110]. As an alternative to battery energy storage installation, the HVDC can be also equipped with additional controller to exploit the energy reserve of nearby flexible voltage-dependent loads to implement primary frequency control or synthetic inertia [111].

Finally, in offshore wind farms connected by an HVDC link to the coast, the inland station can provide synthetic inertia using the kinetic energy of the wind turbines. Although this energy can be obtained by coordinating both HVDC stations, a communication-free strategy is preferred in which the synthetic inertia control extracts energy from the DC line and the other station detects the variation of DC voltage and compensates it by extracting the energy from the turbines [112].

C. Operation with weak grids

Weak grids are electrical systems in which the frequency and voltage amplitude have large variations depending on the operating conditions. The definition of a weak grid involves its impedance and inertia.

Depending on the HVDC technology the interaction with weak grids can be completely different. HVDC systems based on LCC are usually focused on bulk energy transmission and hence there are not designed to be connected to small weak grids. The use of thyristors requires a precise synchronization with the grid frequency and the amplitude of the voltage must be stable for proper polarization of the semiconductors. In weak grids both features are variable, hence the performance of the LCC-HVDC can be affected. On the other hand, the phase angle control couples the active and reactive power and a capacitor bank to provide reactive power compensation is usually designed for the nominal operation. In the case of weak grids, this capacitor can overcompensate reactive power leading to a reduced power factor and increasing the voltage amplitude. Although these drawbacks, it is possible to modify the HVDC station and its control to operate with weak grids if necessary, for example, to power transmission to islands [113].

Alternatively, and hybrid HVDC composed by a CCC-HVDC connected in series with a VSC-HVDC can reduce the

reactive power required by the station allowing its use into weak grids [114].

The preferred choice to connect weak grids is using VSC-HVDC both in GFL and GFM operation. In GFL operation the amount of transferred power is directly linked with the margin of stability, hence in a weak grid there exists a limitation to the transferred power [115]. In this condition, the vector control cannot operate with large power demand, but it can be modified tuning its parameters with a slower dynamics and generating a virtual voltage to improve synchronization [116].

Grid forming operation of VSC-HVDC can provide a more suitable connection to weak grids integrating the HVDC as a power generator which helps to stabilize the grid. A frequency-based synchronization control has been proposed in which the HVDC can provide the nominal power and is not affected by variation in the system frequency. In case of failure, to avoid high currents the internal loop can be switched to vector control [117].

D. HVDC breakers and fault protection

A mechanical switch with a resonant circuit to provide zero crossing current can be employed to implement a DC circuit breaker (DCCB) using a full bridge circuit to simplify the design of the oscillation cycle and provide consecutive interruption capability [118]. Combining surge arresters, mechanical switches, semiconductor devices and current limiters a circuit breaker can be implemented. The precise synchronization of these devices into the DCCB is a key factor to avoid large overvoltages [119].

LCC-HVDC suffer commutation failures which can lead to high currents through the devices and might destroy them. To mitigate this failure a predictive strategy in which the phase angle of the device is modified in order to reduce the effect of the failure has been proposed [120].

VSC-HVDC can provide DC fault capability by changing the design of the submodules in the MMC. However, this alternative allows large currents to circulate through the MMC and increase the costs. The mechanical and semiconductor hybrid DCCB with an active short-circuit path to ground can be used in the MMC providing fast fault current clearance without large current circulating through the submodules [121]. However, the design of hybrid DCCB is complex and has to be evaluated in a large variety of grid conditions, for which fast and precise analytical methods are required [122].

A combination of an ac circuit breaker (ACCB) and the operation of the MMC itself is proposed to manage both ac and dc faults. In the event of ac faults the ACCB operates as its normal operation and for DC faults the converter is configured in a way also the ACCB clears the faults. In order to proper operation this structure requires a fast detection of dc faults [123].

The single-phase to ground is the most common ac fault. In this condition a voltage sag is produced and the MMC requires an strategy to avoid capacitor over-voltages and provide fault tolerant operation isolating the fault from the dc side. Therefore, the power of the HVDC system is not reduced during the failure. A compensation control strategy

can be developed to detect the unbalanced voltages and act over the current references to achieve the mentioned goals [124].

Fault protection in DC systems is challenging because short circuit current has a very fast dynamic. The peak amplitude of the short circuit current is necessary for conventional DCCB and ACCB correct operation. Thus, ultrafast fault detection, location and protection is still a mandatory challenge particularly in HVDC and ESS. Thus, the development of solid-state circuit breakers (SSCB) solutions are designed to meet the challenging protection speed and power density required by future power grid.

VI. CONCLUSION AND FUTURE TRENDS

System level "power electronics" solutions for the electric grid both in the voltage adaptation and power transfer are discussed in a common perspective in the paper. Both the presented technologies shall have the capability to operate in grid-forming mode despite in meshed-grid operation also grid-following mode is requested. Protections are also highlighted as a key technology where a strong interaction with power electronics is expected. The possibility to influence the grid voltage and consequently the power flow and the connected loads is found to be one of the key features of smart transformer and transmission technologies.

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