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OPPORTUNITIES AND CHALLENGES TOWARDS A FURTHER DEPLOYMENT OF FACTS AND HVDC TECHNOLOGIES IN THE EUROPEAN TRANSMISSION SYSTEM CONTEXT

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Abstract: Towards the integration of an increasing penetration of Renewable Energy Sources (RES) generation, the transition pattern in Europe requires careful planning and extensive investments in the electricity system. The needed RES integration especially concerns the electricity grids, as well as the enabling technologies and measures, which can ensure a clean, secure, flexible, and efficient energy supply. In particular, in the context of the integration of large-scale RES generation, the development of adequate HVAC (High Voltage Alternating Current) and HVDC (High Voltage Direct Current) transmission infrastructures and innovative technologies plays an increasingly pivotal role. The technological progress in power electronics over the latest twenty years has contributed to make HVDC more widespread also in terms of new applications. This has also impacted on the development of FACTS (Flexible Alternating Current Transmission System) devices that have recently seen a constant increase in penetration and deployment in the European power system. Both HVDC and FACTS technologies, with their flexibility increase capability, can play a crucial role towards the facilitation of RES integration. Within the European background and considering Italian experiences, the present paper first provides an updated overview of key features and benefits of different FACTS and HVDC technologies. These elements may support the European transmission network planners in their decision-making. Particular attention is devoted to the still open and crucial challenges that regard the further penetration of HVDC and FACTS technologies in the European and Italian system context.

Keywords: Decarbonisation, European power system evolution, FACTS, flexible technologies, HVDC, RES integration, STATCOM, transmission design and planning

INTRODUCTION

Towards the integration of an increasing penetration of Renewable Energy Sources (RES) generation, the transition pattern in Europe, triggered by the ambitious decarbonisation goals set by the European Union (EU) for 2030-2050, requires careful planning and extensive investments in the electricity system, in the framework of the European Energy Union's strategy [1]-[3]. This process also must consider the goal of recovery after the Covid-19 crisis within a new and further changed context, due to the outbreak of war in Ukraine [4][5]. The needed RES integration especially concerns the electricity grids, as well as the enabling technologies and measures, which can ensure a clean, secure, flexible, and efficient energy supply. In this situation, the electrical grid in Europe must adapt to support a low-carbon economy and meet the 2030 and 2050 decarbonization targets [6][7].

The rapid expansion of generation by RES, in particular solar and wind energy, introduces new challenges in maintaining power system stability, reliability, and efficiency. Unlike conventional power plants production, RES-based generation is often intermittent, requiring advanced grid solutions to balance supply and demand in real-time. This has led to a significant focus on improving grid flexibility and resilience through technological innovations [8][9].

To address these challenges, innovative transmission and distribution solutions are being deployed across Europe. Regarding transmission grids, two major technological advancements are central to this modernization:

- High Voltage Direct Current (HVDC) technology [10];
- Flexible Alternating Current Transmission System (FACTS) devices [11].

The technological progress in power electronics over the latest twenty years has contributed to make HVDC more widespread and more attractive over HVAC (High Voltage Alternating Current) for some specific situations, and new HVDC applications have also emerged [8][9]. This has also impacted on the development of FACTS devices that

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have recently seen a constant increase in penetration and deployment in the European power system [12][13].

Both HVDC and FACTS technologies, with their flexibility increase capability, can play a crucial role towards the facilitation of RES integration.

Within the European background and considering Italian experiences, the present paper first provides an updated overview of key features and benefits of different FACTS and HVDC technologies. These elements may support the European transmission network planners in their decision-making. Particular attention is devoted to the still open and crucial challenges that regard the further penetration of HVDC and FACTS technologies in the European and Italian system context. Regarding FACTS, focus is specifically dedicated to STATCOMs (Static Synchronous Compensators) technologies [12][13].

1. STATUS OF HVDC DEVELOPMENTS AND PROJECTS IN EUROPE

Towards the integration of large amounts of electricity produced by RES installations throughout Europe, an attractive grid option for power transmission in more situations is provided by HVDC technology. In the past, HVDC equipment has been deployed due to its features that have made it preferred over conventional HVAC assets for long-distance OHL (overhead line) and USC (undersea cable) power transmission and for asynchronous systems interconnection [10]. The technological progress in power electronics over the latest twenty years has contributed to make HVDC more widespread: in fact, HVDC deployment for the connection and integration of multiple offshore production plants as well as the application of HVDC ties embedded within the different European HVAC synchronous networks have more recently emerged across the pan-European power system as new HVDC implementations [6]-[8]. This leads to enhance transmission flexibility facilitating RES integration into the European power system; however, on the other hand, a more complicated system control management will be necessary.

The different HVDC applications across and around Europe can constitute the base for the mid-to-long term realisation of a potential hybrid HVAC/HVDC pan-European network infrastructure [8][9]. This view is also oriented to bridge the Euro-Mediterranean region power system, considering the HVDC corridors across the Mediterranean basin that are currently under planning and under study [14].

Figure 1 shows the existing HVDC installations and the HVDC projects under construction or planned in the short-to-medium term across Europe, whereas Figure 2, in addition to few HVAC corridors, mostly provides the HVDC projects envisaged in the pan-European system and in the Mediterranean basin up to a long-term time horizon [8][9][14]. Figure 2, based on the Ten-Year Network Development Plan (TYNDP) 2024 of ENTSO-E (European Network of Transmission System Operators for Electricity), shows the projects distinguished by their status according to the following colours: green, for the projects under construction; yellow, for the projects under authorisation; red, for the projects planned but not yet authorised; blue, for the projects under study [9].

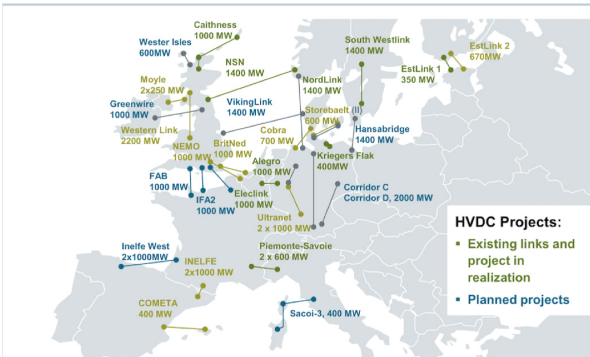

Figure 1: Existing and planned (short-to-medium term) HVDC projects in Europe (derived from [6])

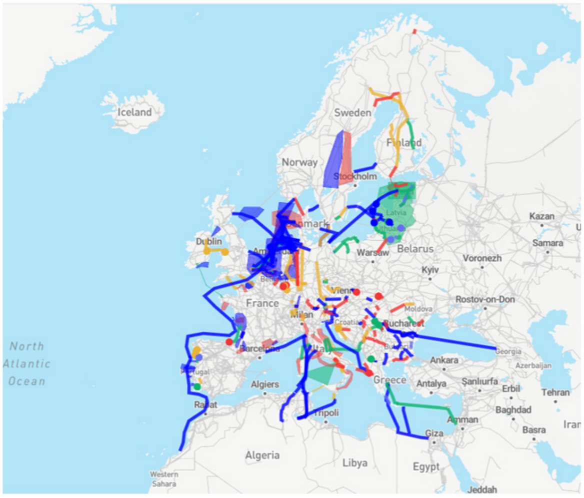

Figure 2: Planned and potential HVAC and HVDC projects (up to a long-term horizon) in Europe and Mediterranean Basin [9]

2. HVDC PROJECTS EXPERIENCE IN ITALY

The implementation of HVDC technology is playing an increasingly central role in the transformation of the European power system, providing solutions for the efficient transmission of electricity over long distances and the interconnection of asynchronous networks.

Figure 3 illustrates the evolution of the HVDC transmission network links in Italy, comparing currently operational HVDC infrastructure with future planned developments. Since the launch of SACOI 2 in 1992, there has been a

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steady expansion of strategic interconnections such as GRITA (Greece-Italy), SAPEI (Sardinia-mainland Italy), and MONITA (Montenegro-Italy), culminating in the recent activation of the FIL (France-Italy Link) between 2022 and 2023 [15]. The latter represents the first HVDC infrastructure in Italy based on the advanced Self-Commutated Voltage Source Converter (VSC) technology, while all other existing HVDC ties across Italy have been realised through the Line-Commutated Current Source Converter (LCC) typology.

Looking ahead to the 2026-2030 timeframe, several new high-capacity interconnections are under construction or planned across different zones of Italian network. The planned ties include SACOI 3, which will modernize the current interconnection between Sardinia, Corsica, and mainland Italy, and GRITA 2, that will strengthen the link with Greece. Particularly significant ties are the ones under construction related to Tyrrhenian Link, which will connect Campania, Sicily, and Sardinia using a 500 kV VSC double bipolar configuration, with each interconnector rated 1000 MW, and the Adriatic Link, which will reinforce the grid between Abruzzo and Marche by a VSC-HVDC transmission capacity of 2×500 MW. Another ongoing expansion project based on VSC-HVDC involves the TUNITA ELMED interconnection (600 MW) between Italy and Tunisia, which will facilitate greater energy exchange with North Africa.

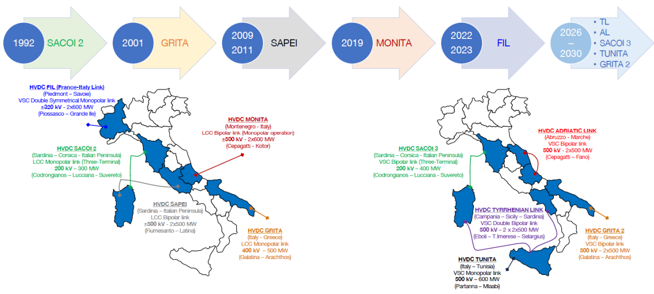

Figure 3: HVDC links in Italy - existing and future installations

Future projects aim to develop a multi-terminal HVDC (MT-HVDC) grid, involving more than two converter stations and incorporating VSC-MMC (Modular Multilevel Converter) technology to ensure more dynamic and flexible energy flow management. However, despite its advantages in terms of efficiency and stability, large-scale HVDC grids adoption still faces technical, economic, and environmental challenges that must be overcome to ensure seamless integration with existing HVAC infrastructures.

It has to be highlighted that the development of MT-HVDC networks is still ongoing as it introduces operational complexities related to system stability and power flow regulation. In this context, Terna has launched the Hypergrid project [15][16], an HVDC infrastructure designed to integrate with existing and future power lines to optimize the operation of current interconnections, reduce environmental impact, and improve the transfer of renewable energy from Southern Italy to the northern regions, where demand is higher. However, the large-scale integration of a MT-HVDC network will only be feasible when HVDC circuit breakers (HVDC CBs) reach sufficient commercial maturity. At present, these devices remain at an experimental stage, with the first prototypes being tested in China [17]. Several manufacturers, mainly in Europe, China, and Japan, are developing solutions with distinct technical characteristics, each offering specific advantages and disadvantages.

To deepen the understanding of these devices, Terna has initiated the development of a low-voltage experimental mock-up for a hybrid HVDC circuit breaker based on SiC (silicon-carbide) MOSFET technology, which offers superior performance compared to traditional silicon-based devices. This prototype will allow real-world testing of system components, avoiding the use of simplified mathematical models and providing concrete data on electromagnetic transients, switching overvoltages, and protection coordination [18].

The technological solutions for overhead lines and converter stations must consider environmental and social sustainability, focusing on minimizing visual impact, footprint, noise, and electromagnetic fields. Another significant challenge is the high cost of HVDC infrastructure, making a thorough cost-benefit analysis essential before launching new projects [16].

From an environmental and social perspective, the expansion of HVDC networks often faces local community opposition, particularly concerning the construction of new converter stations and transmission lines. Even submarine projects, such as the SAPEI interconnection (Italy-Sardinia), while reducing land impact, require comprehensive environmental assessments to ensure that marine ecosystems are not significantly affected.

Therefore, for HVDC to be widely implemented, it is necessary to continue with technological progress and environmental sustainability improvement, while developing advanced regulatory strategies, reducing investment costs, and streamlining coordination among different transmission system operators (TSOs) [15][16].

3. OPEN CHALLENGES ON HVDC DEPLOYMENT PATTERN

HVDC systems have seen a boost in their worldwide application in the last 20 years, mainly due to the rapid technological progress of emerging VSC technology for HVDC converters [30]-[32]. The development of VSC technology has also opened the way to the manufacturing and use of extruded cables as an alternative to the well-proved Mass Impregnated Non-Draining (MIND) cable solution. At the same time, the deployment of VSC technology has pushed the development of bidirectional electrodes, a quite brand-new solution: this needs specific electrical design countermeasures to avoid any damage to the electrode's active parts, since in the past unidirectional electrodes were used. In any case, the real need for bidirectional electrodes came out in recent years when the bipolar scheme of VSC converter started to be commercially available.

Furthermore, recently, the research interest was focused on HVDC Circuit Breakers (HVDC CBs) with the aim to pave the way for HVDC grids [30]. These HVDC CBs can represent a solution to the troubles with VSC half-bridge converters when used with overhead lines. In the past, the HVDC systems were mainly used for bulk power transmission over very distant sites and for long submarine sections as well as modulators for HVAC power flows in different corridors. More recently, new concepts and applications of HVDC transmission have rapidly risen up, in terms of: multi-terminal solutions, that have become the precursor of HVDC grids; embedded ties within synchronous networks, for providing robust support to the existing HVAC grid; interconnections of offshore wind farms. It can be argued that the research hardly kept pace with the boosting HVDC evolution towards those new concepts and applications in these last 20 years.

It is important to outline that the HVDC situation in Europe is quite different from the one in the rest of the world. For example, there are large differences in the HVDC approach from North America to Europe. In this respect, in Europe new technologies for HVDC, and especially for the converter stations, based on VSC, are more and more deployed. Today in Europe, new HVDC corridors are hardly based on LCC technology, whereas on the contrary in the rest of the world the LCC typology is still used for new links, and it is sometimes even the preferred solution. There are different concepts and viewpoints. VSC has gathered its success even before its installations became relevant. Advantages of VSC technology are well known and recognized, especially in terms of flexibility, independent active and reactive power control and voltage regulation [10]; however, VSC complexity and some still missing field returns are among the open questions on the tables of different TSOs. The research on VSC-HVDC is going on considering reliability aspects of the different components, applications in multi-terminal solutions, grid forming, to name few crucial themes. HVDC grids are to be naturally based on VSC technology. In these last 20 years there have been evolutions starting from the symmetric monopole solution formerly with PWM (Pulse Width Modulation) and then with modular multilevel architectures, up to much more traditional bipolar solutions with earth return in monopolar operation. In particular, the bipolar solution of VSC technology will enable in the upcoming years a much more proper comparison with the bipolar LCC technology. In fact, LCC technology is well known with all its limitations and advantages: in the long run of the VSC technology use, a much more robust comparison of the two options will be certainly useful to engineers that have to take a decision.

At the same time, LCC has been preferred for HVDC interties based on overhead lines: in fact, LCC ability to clear temporary faults is faster than the one by VSC. VSC technology is widely used with converters in half-bridge option that does not allow clearing the fault: in such a case, the HVAC circuit breaker shall operate to interrupt the fault current. This implies longer recovery times that may take 1-2 seconds. On the other hand, the LCC technology is able to recover in 250-300 ms the transmission of the same power amount flowing before the temporary fault. It is important to state that a valid VSC converter architecture in this respect would have to be based on the full-bridge or a mixed half-bridge – full-bridge configuration. The former seems to be not yet available, mostly for its larger losses in comparison with the half-bridge option, while the latter has been used outside Europe, especially in China. HVDC CBs would become decisive for the utilization of half-bridge VSC converter option with overhead lines: in such a case, the HVDC CB with a reclosure similar to that one applied in HVAC systems can clear the temporary fault in the overhead line in fast times (possibly in times not shorter than the ones taken by LCC option, since a coordination between HVDC CB and VSC converter bridge becomes necessary). Unfortunately, the HVDC CB is not yet commercially available, also due to cost, stretching area and building volumes, especially for the highest voltage levels. There exist more prototypes that have been tested in research programs, but they are not yet available on the market. Within the standardization bodies, there are debates with the aim to address HVDC CBs qualification even if the approach to such aim does not find a full agreement yet.

An additional field that deserves attention for the VSC converter station is related to the generated electromagnetic interferences. In fact, the switch on time for a transistor, and in particular for a BJT (Bipolar Junction Transistor), is an order of magnitude lower than that one of a thyristor, giving rise to steeper current waveshapes during the commutation process. VSC systems can then give rise to electromagnetic interferences with a higher magnitude and even with a larger frequency range in comparison with those ones generated by LCC systems. For such reasons, specific countermeasures are sometimes needed.

Also, particular attention shall be paid to the qualification procedures that have to be considered specific and dependent on the type of terminal converter stations used (LCC or VSC). VSC converter stations give rise to different overvoltages, both in magnitude and waveshapes, that are different respect to those well-known ones coming from LCC converter stations.

As far as the cable system is concerned, the utilization of extruded solutions is becoming larger and larger, even if there is not a wide experience as with MIND cables. In the 500/525 kV voltage levels for submarine cables for example, the extruded solution has not been installed yet. The first extruded solutions were limited to the maximum conductor temperature of 70 °C, but extruded cable options for higher temperature levels (80 °C - 90 °C) are under development. It has to be highlighted however that higher temperatures mean higher losses and higher voltage drops with obvious consequences in the overall efficiency of the HVDC cable link and larger voltage ranges to be managed at each terminal. Thermoplastic elastomer-based polymers, developed in the latest years for HVDC cables, have become very attractive for their high-level performances comparable to the standard extruded (XLPE, Cross-linked Polyethylene) option, that, on the other hand, requires a longer manufacturing process. Larger developments in the assessment of the HVDC insulation quality have been developed in these last 20 years, especially in the space charge measurements that today can be performed in a full size cable. MIND cables, on the other hand, keep on being a solution considered for the higher reliability, thanks to a consolidated experience. For bulk transmission, especially for submarine links, MIND cables still represent an important and very effective option, featuring a smaller number of factory joints and flexible repair/in field joints.

4. STATUS OF FACTS DEVELOPMENTS AND PROJECTS IN EUROPE

In the latest years, the penetration rate of FACTS installations across Europe has seen a significant increase. This has especially regarded some FACTS devices, such as STATCOMs, in specific countries.

Several STATCOMs have been or are being installed in more European countries in these years, at the transmission but also at the distribution and industrial non-utility levels, given the ongoing pattern for a continuously rising RES integration need in view of the ambitious decarbonization (EU and national) targets for 2030–2050 [6][9][19]. The ongoing shift in the energy mix, with the power generation affected by the phase out of traditional thermoelectric plants and the widespread installation of RES units, results in a lack of reactive power support demanded by the grid operators to address voltage variations [8][9]. At the transmission level, most STATCOMs in Europe have been installed over the years in the United Kingdom (UK) - especially in England and Scotland - often coupled to onshore wind and especially offshore power plants for grid voltage stabilization. Key STATCOM installations have been realised in this sense in previous years in the UK for the Thanet (2x ± 35 MVAr in parallel for a total 300 MW offshore power capacity), Greater Gabbard (3x ± 50 MVAr in parallel for a total 504 MW offshore power capacity) and London Array (4x ± 50 MVAr in parallel for a total 630 MW offshore power capacity) projects [20].

More recently, the 1.2 GW Hornsea ONE offshore windfarm installation in the UK North Sea, completed in 2020, features 3x ± 200 MVAr STATCOMs [20]. Also, further ongoing offshore windfarm projects under development in the UK and in North Sea waters may need the installation of STATCOMs for onshore grid support and voltage stabilization [20][24]. Some hybrid combinations of STATCOMs, in parallel with mechanical and/or thyristor-switched devices (capacitors, reactors), have been installed as well. In this sense, a large STATCOM scheme was made operational in 2020 in three sites in the UK to also support HVDC interconnectors with Europe: the scheme is based on three separate hybrid STATCOM units in the British substations in Bolney, Ninfield and Richborough. In this way, it is possible to provide the HVAC network with fast response support and enhance regional voltage stability for the UK–Belgium HVDC interconnection through the ability to deliver a dynamic reactive power in the range −300 ÷ +675 MVAr (with availability level of 95% required by the customer) [20][24]. More STATCOMs have been and are being installed in Germany as well. One of the pioneering STATCOM applications was completed and commissioned in Borken in 2020, where the first German hybrid STATCOM facility was put into operation to dynamically support the voltage and enhance the power quality at 380 kV level, within a range −250 ÷ +400 MVAr [21].

In Germany, to ensure voltage stability and support the reactive powering of a framework of very ambitious and massive RES penetration targets (80% of energy demand shall be covered from RES by 2050), all four German TSOs aim to install tens STATCOMs by 2030 [22]. This reflects the combination of factors, especially affecting the German transmission network, such as the constant increase in reactive power demand due to the higher transmission line loading, the expansion of the bulk power system as well as market-driven effects. These issues have urged the German TSOs to put in place some measures upon calculating a minimum condition requirement for controllable reactive power compensators in their grid development plan. This led in 2020 to specifying the need for an additional reactive controllable capacity in the range between 23 GVAr and 28 GVAr in the whole future German grid [22]. This very high demand of controllable reactive power must be covered mostly by STATCOMs. To minimize the number of devices to be installed and to optimize their use, the German TSOs have estimated that it will be necessary to install future STATCOMs with ratings in a range 250 to 600 Mvar per system [22].

Within this context, in the grid of the German TSO Amprion, three STATCOMs, each having a capacity of ±600 Mvar, have been/are being installed at Mannheim-Rheinau, Polsum and Lampertheim substations, whereas a ±300 Mvar STATCOM is being commissioned at the network node in Wehrendorf [22]. These four STATCOMs in Amprion's system are due to be completed and put in operation by 2024-2025. Also, in the grid of the German TSO 50Hertz, two ±300 Mvar STATCOM systems will be installed in 2025–2027 as hybrid solutions in Bad Lauchstädt substation, which is located within the 50Hertz grid area and is crucial for the transport of increasing quotas of electricity from RES [22][25].

The German TSOs have also importantly highlighted the need to equip power electronics converters used for RES connection with grid-forming capability (by voltage injection) in order to avoid stability issues. In fact, stable system operation is only possible up to a certain ratio of today's grid-following or grid-supporting (by current injection) converters [22]. For this issue, the German TSOs strongly advise that all new converters (for STATCOMs but also for VSC-HVDC and for RES connection) linked to the transmission system shall be exclusively equipped with a grid-forming control option [22]. In this sense, the first grid-forming STATCOM in Germany was recently (2024) installed in Opladen substation at the 380 kV level with a reactive power rating of ±300 Mvar (in Amprion's grid) [25]. In addition to the grid-forming capabilities, for future developments of STATCOMs, the final recommendation of the German TSOs regards the need to expand the limited energy reserves in the capacitors of the converter modules to provide a certain share of inertia and contribute to meeting the future system needs, e.g., by coupling with storage devices such as supercapacitors to form E-STATCOMs. In this sense, Amprion plans five to nine additional grid-forming units in the coming years [25].

Regarding the developments in Italy, in the latest years, a need has emerged to improve voltage and reactive power support as well as to increase system stability in some critical nodes of the Italian transmission grid. For this reason, the Italian TSO Terna has ordered and installed some STATCOMs for grid stabilization. In the years 2021–2022, the first three STATCOMs were planned and commissioned; they are located in Villanova (Abruzzo region), Latina (Latium region) and Galatina (Apulia region), and they are all rated ±125 Mvar [26][27]. The location of the first three STATCOMs in the Italian power grid was chosen because of the need of reactive power support and voltage stability that those devices can smoothly and dynamically address in those network nodes at the interfaces with LCC-based HVDC stations. This regards specifically: Villanova, terminal station of the MONITA link (Montenegro – Italy); Latina, terminal station of the SAPEI HVDC link (Sardinia – mainland Italy); Galatina, terminal station of the GRITA (Greece – Italy) HVDC link.

In 2023, additional two STATCOMs (rated ±125 Mvar each as well) were further installed and implemented in Aurelia and Montalto nodes (in Latium region), to cope for the foreseen shutdown of a large (1980 MW) coal-fired power plant [26]. Figure 4 maps the installation locations of the five STATCOMs in the Italian transmission system [26][27].

The new STATCOM devices are able to smoothen voltage fluctuations by injecting or absorbing reactive power in the Italian grid, depending on the system conditions and requirements. The installed STATCOM systems aim to significantly limit voltage imbalances, drops and instability. Further STATCOM devices may be installed in the Italian system in the near future (before 2030).

Figure 4: Localization of the five STATCOMs in the Italian transmission grid [26]

All installed STATCOM devices are connected to the 380 kV transmission grid.e

In comparison with an equivalent rating Synchronous Condenser, a STATCOM may need a higher footprint. For this reason, STATCOM devices are often installed using space-saving containerized solutions; in this case, each valve phase is installed in a dedicated container, allowing for fast commissioning and easy maintenance.

5. OPEN CHALLENGES ON FACTS DEPLOYMENT PATTERN: THE EXPERIENCE IN EUROPE AND IN ITALY

Among the various FACTS devices, STATCOMs represent one of the most advanced and flexible solutions for voltage and reactive power control, providing a fast and dynamic response to load and generation fluctuations [12][25].

For a widespread adoption of the STATCOM solution, procurement, maintainability and standardization represent critical issues.

From a technical perspective, the design and integration of STATCOMs must consider various parameters, including grid nominal voltage, reactive power regulation capability, and compatibility with existing HVAC infrastructure. In Italy, Terna has adopted a standardized approach to STATCOM implementation to optimize maintenance costs and reduce commissioning times [15][26].

The design of Terna's STATCOM installations is based on specific technical requirements to ensure high efficiency, modularity, and operational reliability. A fundamental element of this standardization is the 125 MVA, 380 kV/35 kV step-up transformer, which features a 12.5% short-circuit impedance. Terna's STATCOM transformers share identical electro-mechanical interfaces with civil works and other equipment, enabling a multi-vendor approach and optimal spare parts management [27].

The system adopts a Modular Multilevel Converter (MMC) in full-bridge topology, which guarantees both high efficiency and flexibility. The valve units, arranged in a delta connection, incorporate integrated damping reactors, improving the dynamic response of the system. Additionally, pre-charge resistances are implemented to limit inrush currents during start-up and are bypassed once the STATCOM reaches full operation.

This modular approach ensures an optimal balance between operational efficiency and cost-effectiveness, making STATCOMs a reliable and scalable solution for voltage stabilization in the Italian power grid.

6. IMPACT OF STATCOM TECHNOLOGY: ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

STATCOMs play a crucial role in reducing CO_2 emissions by facilitating greater RES penetration while minimizing reliance on fossil fuel-based generation [6][9]. Additionally:

- compact footprint allows installation within existing substations, avoiding new infrastructure development [26];
- lower energy losses compared to traditional reactive power compensation solutions can be achieved [12][28];
- faster dynamic response (<40 ms), ensuring better grid stability, reduces the need for supplementary power sources during voltage fluctuations [12][25].

STATCOMs may present a reduced footprint and low noise, thus minimizing the environmental impact.

The standardization of STATCOM technology by Terna aims to optimize investment and maintenance costs, while improving system reliability [15][26]:

- the investment for five STATCOMs (Latina, Galatina, Villanova, Aurelia, and Montalto) amounts to 112 M€ ca. (including civil works, substation bays, spare parts) [27][28];
- compared to traditional synchronous condensers, STATCOMs feature lower maintenance costs and reduced commissioning time, thanks to their modular design (however, they do not provide short circuit power and inertia, unless advanced solutions based on E-STATCOMs are deployed);
- STATCOMs help prevent costly blackouts by dynamically adjusting reactive power and stabilizing voltage fluctuations in real time.

This combination of economic and environmental benefits makes STATCOMs a crucial asset for reactive power/voltage control supporting the transition toward a more sustainable, resilient, and efficient grid [15][17][24].

The single line diagram of a Terna standardized STATCOM project is reported in Figure 5. Two installation examples are reported in Figure 6 and in Figure 7.

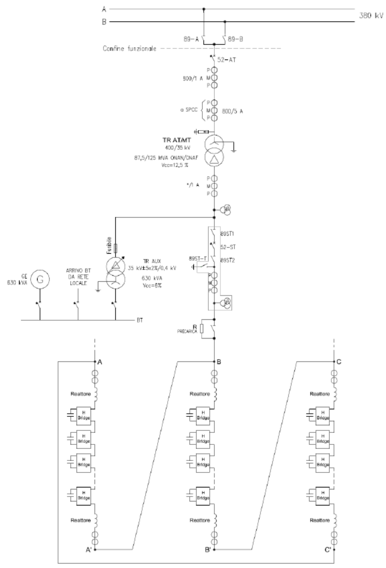

Figure 5: STATCOM single line diagram

Figure 6: Terna's containerized solution for STATCOM arrangement (left side: Aurelia substation, by NIDEC, using Hybrid Switchgear; right side: Latina Substation, by SIEMENS, using air insulated switchgear)

Figure 7: Terna's indoor solution for STATCOM arrangement (Galatina substation, by NIDEC)

7. CONCLUSION AND FUTURE OUTLOOK

As Europe advances towards its decarbonization targets, the integration of FACTS and HVDC technologies will be essential for ensuring grid stability, flexibility, and efficiency. New HVDC interconnections (both cross-border and internal) are expected to provide for increased power transmission capacity towards RES integration. Different technological challenges will have to be addressed, in order to realise the long-term vision of hybrid HVAC/HVDC grids, in Europe and in Italy as well. At the same time, FACTS are expected to provide grid support, coping with the shutdown of large thermal power plants. In this sense, the installation of several STATCOMs solutions is aimed at performing voltage / reactive power regulation, enabling for greater RES penetration, while optimizing the economic and environmental footprint of the transmission network.

The use of modular and standardized solutions enables lower costs and shorter procurement times, while enhancing maintainability and spare parts management [29].

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