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Review

Comparison of Advanced Flexible Alternating Current Transmission System (FACTS) Devices with Conventional Technologies for Power System Stability Enhancement: An Updated Review †

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Abstract: The continuously growing penetration of renewable energy sources (RESs) in electrical networks provides increasing challenges and critical situations to be managed by worldwide system operators. Due to their features and variability, non-programmable RES power plants, whose increasing penetration reduces the inertia level of the power system, may determine the instability effects on the grids, especially from the frequency and voltage regulation standpoints. The present study focuses on the support that advanced FACTS (Flexible Alternating Current Transmission System) devices, such as STATCOMs (Static Synchronous Compensators), can provide to the power system operation in terms of system inertia improvement, frequency stability, and voltage stability. In particular, a review of the scientific literature and practice is performed, with the aim of benchmarking the ongoing evolution of these technologies, also comparing them with different options based on synchronous condensers, synchronous condensers integrated with flywheels, and STATCOMs with supercapacitors. The outcome of the analysis consists of an updated evaluation of the state-of-the-art technological development in the field and of a comparison between different FACTSs with the purpose of identifying the most suitable solutions for different practical situations, also taking account of synergies across various options. This study includes an updated overview regarding the status of STATCOM installation in the Italian power grid.

Keywords: FACTS; STATCOM; VSC; SC; RES integration

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1. Introduction

As widely discussed in the technical literature, most of the industrialized countries in the world are operating an energy transition from fossil fuels to renewable energy sources in their electrical networks. This determines several adapting troubles in worldwide grids, which require an improvement in power system stability [1,2].

On one hand, in order to exploit regions characterized by high levels of wind or sunlight, a huge amount of renewable power is being installed in relatively small portions of the electrical grids, determining power transmission line congestions.

On the other hand, in order to exploit the photovoltaic power at a local level, the presence of Distributed Energy Resources (DER) is also growing rapidly, so that the traditional top-down structure of the electrical networks, characterized by a passive distribution grid, is progressively changing, introducing active distribution grids characterized by a high penetration of DERs (Figure 1).

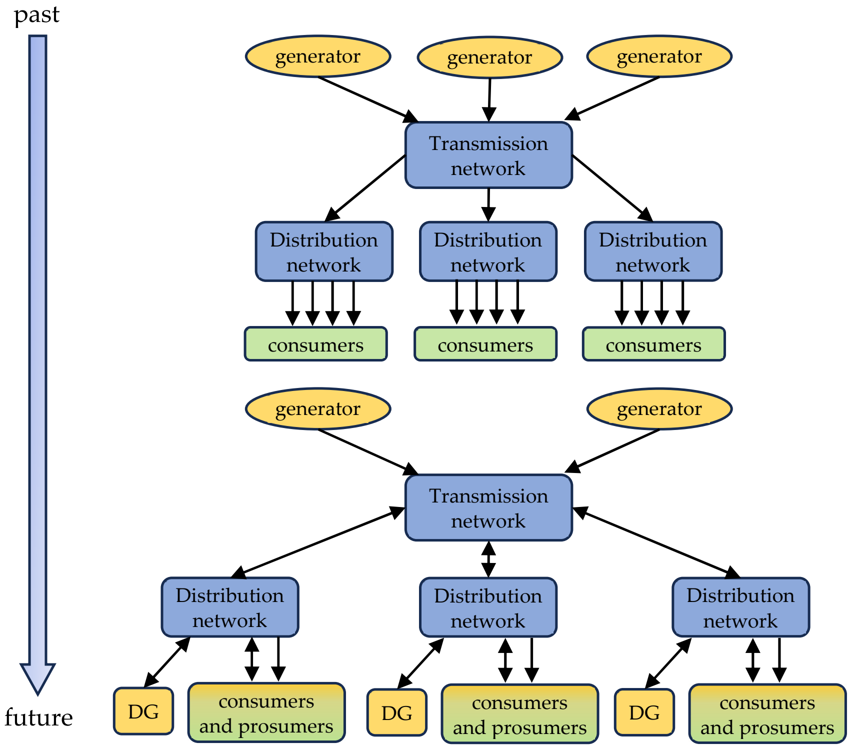

Figure 1. Power system structure evolution, from the past to the future.

This reconfiguration is a call to the creation of a new bulk power system paradigm, to manage and avoid critical scenarios, such as cascade events and blackouts, also by adopting new configurations for the actual restoration plans [3,4].

Moreover, the progressive substitution of traditional power generators with wind and photovoltaic power facilities impacts on the steady-state stability of electrical networks by affecting both the network frequency and voltage regulations. On the side of the frequency regulation, the rotational inertia which characterizes synchronous generators is one of the most important aspects to support the network frequency regulation following a power disturbance. In this context, solar panels are inertia-less devices, and the wind turbines are interfaced with the grid by means of converters, which decouple the wind generator from the network [2]. Hence, neither photovoltaic farms nor wind ones are able to provide an inertial response in the case of significant network frequency variations, so as to weaken the transient stability of the power systems. On the side of voltage regulation in the electrical networks, the non-programmability of renewable energy sources (RESs) makes it more complex to maintain constant voltage levels and to guarantee the suitable active and reactive power transfer.

For example, consistent with such a scenario, according to the Italian TSO, Terna, the Italian electricity grid presents the following critical issues [5]:

- A progressive reduction in the regulating power and of inertia, for the modification of the operating structure of the generation park, with less and less presence in service of programmable rotating capacity;
- An increase in network congestion related to non-homogeneous development of RESs;
- A strong tightening of the voltage regulation problems (overvoltages and voltage dips) and instability of frequency (fluctuations and uncontrolled grid separations), already experienced in recent years.

Through an in-depth review of the scientific literature, this work aims to expound which device typologies are able to effectively support the network in terms of frequency and voltage stability and power quality.

This analysis regards both relatively recent technologies, such as SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator) and more traditional ones, which include synchronous compensators. Moreover, the synergy between different technologies [6] is considered.

2. Recall on the Role of Inertia in the Frequency Regulation Process

The meaning of inertia H_{sys} in a power system is the capacity of the system to withstand perturbations, such as a sudden unbalance between load and generation, without determining an excessive oscillation of the grid frequency [5]. It is strictly related to the moment of inertia of the synchronous machine's rotating masses [7] and to the total apparent power of the synchronous machines [8]. It can be defined as follows:

$$H = \frac{J\omega_r^2}{2S} = \frac{E_{SG}}{S} \quad (1)$$

with:

- J the moment of inertia of the rotor;
- ω_r the angular speed;
- S the apparent power of the machine;
- E_{SG} the kinetic energy stored in the turbine and generator [8].

In the power system context, the inertia H_{sys}, which is strictly related to the total apparent power of the synchronous machines, can be defined as:

$$H_{sys} = \frac{\sum_{i=1}^{N}(S_i H_i)}{S_{sys}} \quad (2)$$

with:

- S_{sys} the total generation capacity;
- N the number of synchronous machines connected to the network;
- S_i the nominal apparent power of the ith synchronous machine;
- H_i the constant of inertia of the ith synchronous machine.

Moreover, it is worth considering which is the frequency time derivative (*df/dt*) during a perturbation, expressed by the Rate of Change of Frequency (ROCOF), expressed in Hz/s [9], which is directly related to the inertia of the system.

If the electric load or the generation changes suddenly, the initial ROCOF is related to the time instants immediately after the disconnection of either a generator or load from the network, before any controls become active. It represents the highest ROCOF of the system and it is possible to compute its average value, by considering N synchronous loads and generators, as follows:

$$\left.\frac{d\Delta f}{dt}\right|_{t=0^+} = \frac{f^0 P_k}{2\sum_{i=1, i\neq k}^{N} H_i S_i} = \frac{f^0 P_k}{2H_{sys}S_{sys}} \quad (3)$$

with:

- Δf the frequency deviation from its nominal value f^0;
- 0^+ the moment immediately after disconnection of the electric load or generation;
- P_k the lost electric generation or load (the machine carrying the index k);
- H_i constant of inertia:
- S_i the apparent power rating of the synchronous machine i, where i varies from 1 to N.

Therefore, the system inertia is strictly related to the amount of rotating machines in operation in the considered network and to the constant inertia H_i of each machine. In the first seconds after a disturbance, the inertia constant H_{sys} of the system plays a fundamental role.

Considering two systems with different values of inertia (Figure 2) and thinking about (3), we can make the following considerations:

- Systems which present a high level of ROCOF are characterized by a low value of inertia, making it necessary to adopt fast frequency regulation systems to avoid critical situations.
- The minimum frequency reached after a disturbance event in systems with a low inertia value, i.e., the nadir of the system, is lower compared to systems with a higher inertia level. This means that a low level of inertia makes it easier to reach critically low levels of frequency, which could compromise the power system stability [5].

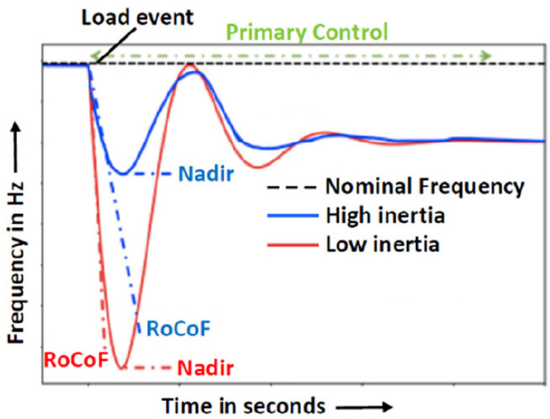

Figure 2. Frequency response with high and low inertia [10].

Three main frequency regulation reserves are defined at the European level, namely, the primary, secondary, and tertiary reserves [11]. Thanks to such reserves, TSOs are able to perform frequency regulation actions. Figure 3 shows the technical characteristics of the three frequency regulation reserves planned for the Italian network, in accordance with the Italian grid code. From Figure 3, it is possible to note the relevant activation time and the minimum required duration of such reserves. Their main purposes can be summarized as follows:

- ***Primary control*** is based on automatic actions that act from the first seconds following the variation in the frequency by means of automatic regulators on board the electric generators (automatic regulation device able to modulate the delivered power). This regulation aims to give an initial response to the imbalance between generated and absorbed powers and to stop the consequent variation in the frequency, but not to restore the frequency to its nominal value, due to the drop in the regulators.
- ***Secondary control*** is based on automatic actions and has the purpose of bringing the frequency back to its nominal value; it intervenes with slower times of the order of tens of seconds.
- ***Tertiary control***, unlike the previous ones, is carried out at Terna's request (no automatic actions are envisaged), to restore reserves.

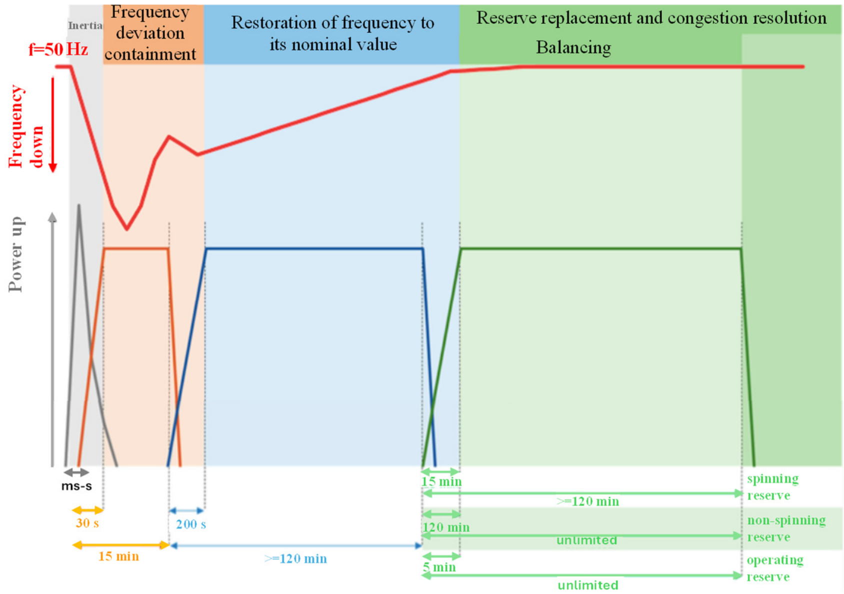

Figure 3. Schematic diagram of the frequency regulation as a function of the intervention time [11].

3. Conventional and FACTS Devices for Improving Network Inertia

In this section, the available technological solutions to support the frequency regulation of electrical grids are presented, considering the pros and cons of both FACTS devices and more conventional options.

3.1. Synchronous Condenser with Flywheel (SCF)

In order to counteract the decrease in both the network inertia and fault level [12,13], one of the most effective solutions is represented by synchronous condenser flywheel (SCF) systems. Such devices are characterized by a higher inertia constant (typically H = 7 s), compared to conventional synchronous condensers (SCs) (H = 1.25–2). Hence, despite their simple control system, they can generate transient active power to boost system inertia more significantly than SC, and they will enable a safe and reliable grid operation despite the intensive growth in RES. In this context, the Italian TSO considers equipping some SCs with additional flywheels in the Sardinia network: two SCFs are under construction in a 400 kV substation in a southern area of Sardinia. These SCFs represent a benchmark for other future installations in the rest of Italy planned for the next years.

The main requirements identified by Terna for SCFs are as follows:

- Solid-rotor 3000 rpm units;
- A rated power of +250/−125 MVAr, with a 19 kV rated voltage;
- Temporary overload up to 375 MVAr for 30 s and 500 MVAr for 10 s;
- Inertia constant H = 7 s, corresponding to a 35,500 kg·m^2 moment of inertia, thanks to an attached flywheel installed in a vacuum chamber;
- Subtransient reactance equal to 14% (unsaturated)/10% (saturated);
- 400 kV/19 kV step-up transformers with a size of 290 MVA.

The flywheel helps to enhance the inertia contribution to H = 7 s (corresponding to a 35,500 kg·m^2 moment of inertia), operates in a vacuum enclosure, and is directly keyed on the main shaft of the generator. The vacuum chamber helps to reduce the friction and cooling losses to minimal values. The total SCF losses in nominal conditions are less than 3 MW. The footprint of a single SCF is close to 2400 m^2. The unitary price for three SCFs is close to 25 M€, comprising maintenance for 10 years.

The nominal power of the SCFs is determined by the cooling system for large generators, a technological limitation, which, until now, can be overcome only by a few suppliers in Europe. In contrast, the flywheel size is constrained by mechanical factors, such as stress on the SCF shaft in the case of close-in short circuits. The design criterion for the flywheel is based on the minimum equivalent inertia, J_{eq}, which ensures that the ROCOF remains below the threshold required for the safe operation network-connected renewable energy converters, as described by this expression:

$$J_{eq} = \frac{\Delta P}{f_n \left(\frac{2\pi}{p}\right)^2 ROCOF_{max}} \tag{4}$$

being ΔP the active power deviation allowed in normal operations, p the pole pairs of the SCF, and f_n the reference frequency. Expression (4) ignores the self-regulating behavior of consumers, in terms of frequency or voltage deviations, leading to conservative assumptions.

The SCF layout is defined as shown in Figure 4 by using a 3D CAD representation.

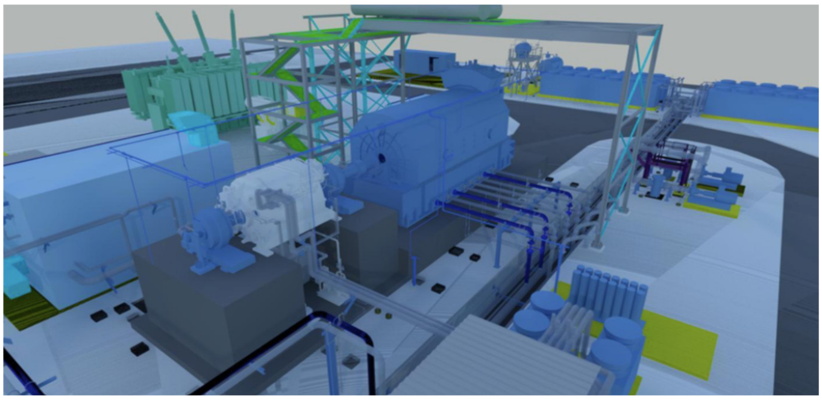

Figure 4. A 3D Cad representation of the SCF layout [12].

In [12], a power disturbance ΔP = 800 MW consisting of a single-phase fault in the Sardinia High Voltage (HV) was simulated. The simulations were performed in a scenario with no carbon emissions (all coal-based power units were cut off) with a total load demand of 1000 MW and a $ROCOF_{max}$ = 2.5 Hz/s. In this specific scenario, the Sardinia network has a very low fault level (for the lack of large synchronous generators), so a fault at the network HV level could easily trigger HVDC commutation failures (CFs). At first, all the SCs and SCFs are considered in service. Figure 5 shows the benefit of using SCF in this context. In particular, if a fault occurs in a central point of the Sardinia network, and if it is cleared in 100 ms by line breakers, the nominal conditions are restored after a significant but not harmful transience (Figure 5a). The simulated fault occurs at t = 5 s and is cleared after 100 ms. Conversely, without any SCFs in service, a fault may provoke a frequency collapse, leading to a blackout (Figure 5b).

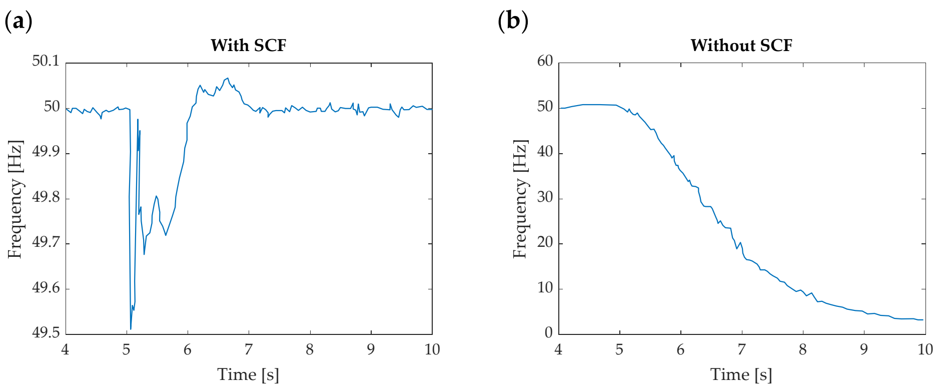

Figure 5. Frequency in the Sardinia network for single-phase fault in the 150 kV grid of central Sardinia. (**a**) All SCFSs and SCs are in normal operation; (**b**) SCFs are out of service [12].

3.2. Virtual Synchronous Machine (VSM)

A Virtual Synchronous Machine (VSM) can be seen as a power converter, which, by means of proper control, can dynamically behave like a synchronous generator, as seen from the network point of connection. It can provide inertia and damping properties to the system [14] (Figure 6).

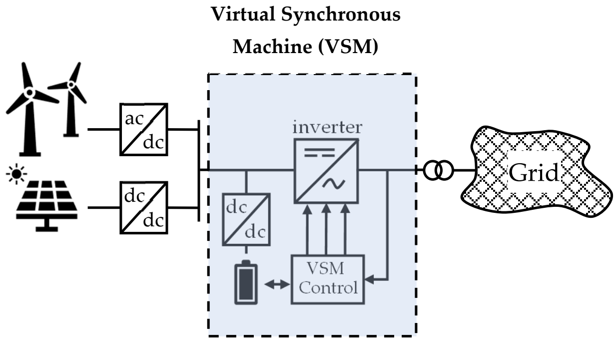

Figure 6. An overall representation of a VSM.

The power converters, decoupling the RES generators from the network, are in fact generally not operated to handle grid frequency variations. On the other hand, the converter regulator can precisely control the energy exchange with the network by recording the network frequency displacement [15]. This energy exchange can be labelled synthetic (or virtual) inertial behavior and is identified by a synthetic inertial moment J_V. When both converters and SCs are coexistent in a power system and they provide an inertial contribution, the system inertial constant H_{sys} can be expressed as:

$$H_{sys} = \frac{\sum \frac{J_V \cdot \omega^2}{2} + \sum E_{SG}}{S_{sys}} = \frac{\sum E_V + \sum E_{SG}}{S_{sys}} \tag{5}$$

Since converters electrically decouple the generating unit from the network, in principle, any type of energy collector or power source can be adopted to provide inertial support to the system (e.g., supercapacitors, storage systems and flywheels). For example, in wind turbines, the kinetic energy provided by the rotating blades, gearbox, and generator contributes to the total inertia of the system. In a photovoltaic system (PVS), batteries can be connected as a supplementary storage system.

The VSM control is designed to provide the following services:

- Enable stable operation with high penetration of RES;
- Provide synthetic inertia for the power system frequency regulation;
- Minimize the frequency nadir and the ROCOF of the system.
- Enhance the stability control for low-inertia and weak grid connections;

The different approaches for the VSM control are, for most, based on the emulation of the swing equation of a synchronous generator, as depicted in Figure 7.

The expression of the accelerating power of a VSM can be derived by the differentiation of the kinetic energy of the rotating masses of a synchronous generator in this way:

$$\frac{dE_{SG}}{dt} = J\omega_r \frac{d\omega_r}{dt} \tag{6}$$

If the angular speed remains around the nominal angular synchronous speed ω_{r_0} [rad/s] and all variables are expressed in a per-unit system, the emulated swing equation of a VSM can be expressed as follows:

$$P_m - P_e = 2H\frac{d\omega_r}{dt} + P_D \tag{7}$$

$$\frac{d\delta}{dt} = \omega_r - \omega_g \tag{8}$$

$$P_D = K_d(\omega_r - \omega_g) \tag{9}$$

where P_m is the mechanical power provided by the prime mover, P_e is the output power, $P_D = K_d(\omega_r - \omega_g)$ is the damping power, which serves to reproduce the effect of damper windings of a synchronous generator useful to dampen the grid frequency oscillations, and K_d is the well-known damping coefficient. Furthermore, δ, ω_r, and ω_g, are the rotor angle, the rotor angular speed, and the reference rotor angular speed of the grid, respectively. It is worth noting that in practical application, ω_g is not always accessible. Thus, the damping control loop is difficult to implement without remote points of measurement or with a wide area monitoring system.

The implementation of Equation (7) in the VSM control makes the power converter behave like a synchronous generator connected to the network. Figure 8 represents a block diagram of the VSM control emulating the behavior of a synchronous machine according to Equation (7).

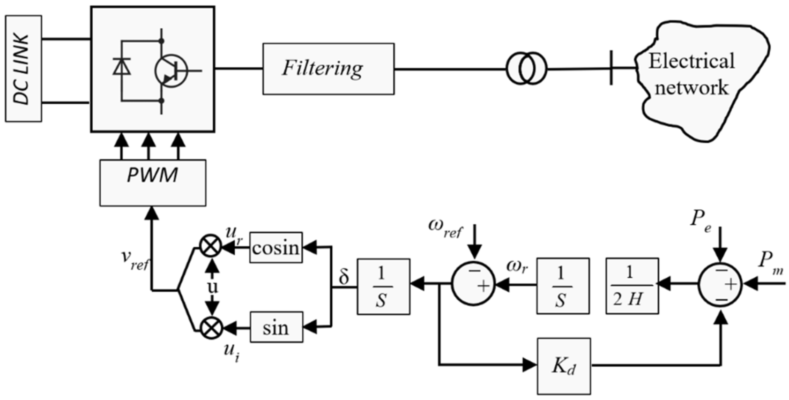

Figure 7. VSM control structure and grid integration.

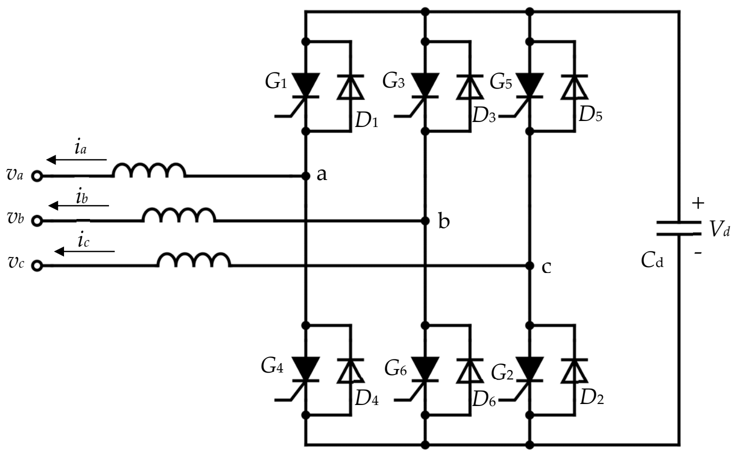

Figure 8. Circuit diagram of a simple STATCOM.

3.3. VSC STATCOM

A STATCOM can be viewed as a controlled source of reactive power, typically comprising a DC link and a voltage source converter (VSC) connected to the grid with a shunt transformer [16] (Figure 8). It can supply capacitive or inductive reactive power for voltage regulation purposes and is used to reduce the harmonic content of the current and voltage waves. Due to its superior features with respect to SVC, STATCOM is given more emphasis in this review. Theoretically, in a balanced system where a STATCOM with a three-phase converter is controlling only reactive power, the capacitor of the DC link of a STATCOM could have a capacitance of zero Farads. This is because the reactive power delivered to the system does not increase the active power exchange between the DC and AC sides [8]. In any case, in practical STATCOMs, a small capacitor is necessary to stabilize or control the DC side voltage, as it is subjected to fluctuations during the switch commutations.

As regards the constant inertia of the STATCOM, an equivalent parameter, H_{ST}, can be defined by:

$$H_{ST} = \frac{CV_{DC}^2}{2S_{ST}} \tag{10}$$

where S_{ST} is the STATCOM apparent power, C is the DC capacitance and V_{DC} is its voltage.

The constant H_{ST} is a measure of the amount of stored energy in the capacitance of the device, similar to the constant H defined in (1), which can be associated with the kinetic energy of the rotor of the synchronous generator. For synchronous machines, the value of H is typically a few seconds (generally between 1 and 3 s); differently, for STATCOMs, the value of H_{ST} ranges from milliseconds to less than 5 milliseconds (0.5–5 ms) when controlling only reactive power. This indicates that the three-phase converter-based STATCOM has minimal stored energy in its DC capacitor when designed only for reactive power control (which is the common case).

In contrast, the stored energy in the DC capacitor of STATCOMs based on a cascaded multilevel inverter (CMI) is larger (Figure 9). Consequently, if properly tuned, CMI STATCOM could also contribute to inertia frequency support by regulating the voltage of the DC link during abnormal conditions.

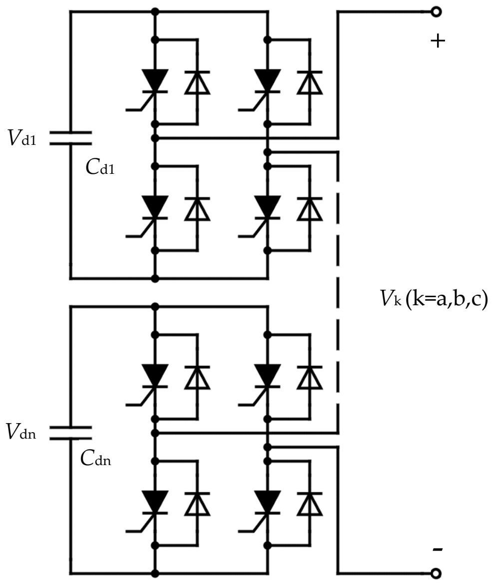

Figure 9. Cascade converter basic topology.

In other words, a CMI-based STATCOM can function as a VSM. The following relationship can be written to estimate the inertia constant of a CMI-STATCOM [16]:

$$H_{ST} = \frac{CN\left(V_{DC\_MAX}^2 - V_{DC\_MIN}^2\right)}{2S_{ST}} \tag{11}$$

where V_{DC_MAX}, V_{DC_MIN} represent the maximum and the minimum levels of V_{DC}, respectively, and N represents the number of CMI per phase. In the case study presented in [16], H_{ST} = 20 ms. This value is higher with respect to the stand-alone STATCOM, but still the inertial contribution of a CMI-STATCOM can be considered negligible. Table 1 compares the main features of a CMI-based STATCOM and an SC.

Table 1. Comparison between CMI-based STATCOM and SC [12,13].

Characteristics	SC	CMI-STATCOM
Reactive Power Capability	Inductive output ~60% of capacitive output	Same inductive and capacitive output
Overload Capability	Very good capacitive overload	Limited by time and amount
Response Time to sudden voltage changes (s)	Immediately	0.03–0.04
Response Time to control actions (s)	1–3	0.03–0.04
H (s)	~1.25–2	~0.01–0.02
Contribution to system short-circuit power	Yes	Negligible

The main difference between a STATCOM and an SC relies on the fact that the former behaves as a fast current source, while the latter acts as a slow voltage source. This allows the STATCOM to achieve any targeted current output within its capability in less than two cycles. It can also provide both inductive and capacitive reactive contribution. In the case of a sudden voltage deviation, the SC can react immediately by supplying current proportional to the voltage variation, regardless of the control actions. However, its response time to control commands is approximately 1–3 s. Additionally, the maximum allowable frequency deviation for SCs is limited and fixed by the system, as they are synchronized with the network. In contrast, solutions like STATCOMs can deliver active power, regardless of the frequency deviation occurring in the network.

3.4. STATCOM with Supercapacitors

Another method to increase the inertia constant of a STATCOM is to connect an energy storage system (ESS), specifically a supercapacitor system (SCESS), to its DC link (Figure 10) [17–20]. This integrated device is also called Energy Storage Enhanced STATCOM (E-STATCOM or ES-STATCOM) [21,22].

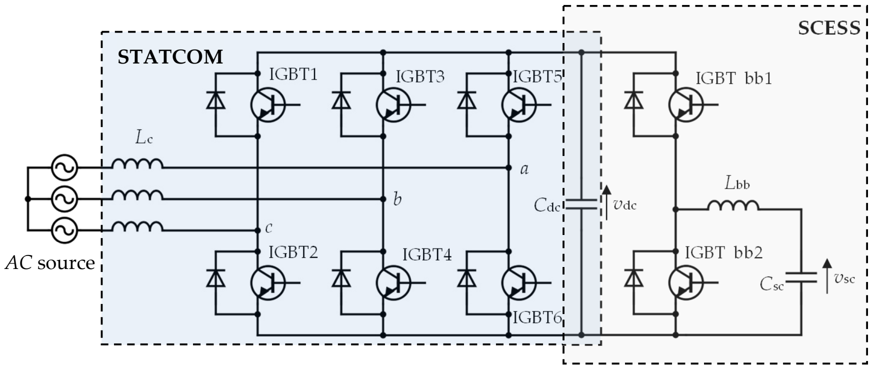

Figure 10. Diagram of an E-STATCOM.

The SCESS system is directly connected to the STATCOM DC link. Its presence modifies the voltage of the DC link to inject active power into the network. When the STATCOM intervenes with an active power injection, the supercapacitors discharge energy by lowering the voltage of the DC link and by exchanging energy with the grid. The STATCOM operation is stopped if the voltage of the DC link falls below the peak line-to-line AC value. A bi-directional DC-DC converter is used to interface the supercapacitors with the STATCOM's DC link in order to keep the DC voltage as constant as possible during energy export.

Some recent discoveries in material manufacturing have led the SCESS to emerge as a key technology for high-power utilities and as a performing energy storage device for energy-intensive applications. In terms of dynamic performance, supercapacitors have faster charge and discharge cycles than batteries over their lifetime and can be recharged as quickly as they are discharged. They also have a significantly longer lifecycle than batteries. Moreover, although batteries are cost effective and available in a large size range, their maintenance requirements, temperature sensitivity, and limited cycle life make them less attractive for burst power applications, i.e., for installations which require rapid charge/discharge behavior.

STATCOMs require an energy storage device with a high energy content, depending on the discharge rate. Batteries are characterized by a high energy content with long-term discharge (in the order of tens of minutes). Instead, for short-term discharge (within one minute), the same battery can release 10-times-lower energy. On the contrary, for the same short-term discharge time, supercapacitors have a two-times-higher energy content.

In Table 2, there is a comparison in relative terms of the costs and footprint between a commercial STATCOM that uses supercapacitors and a STATCOM equipped with Li-ion batteries.

Table 2. Relative comparison of investment costs and surface/area for a STATCOM equipped with different storage technologies for short-time applications [23].

50 MVA Solution	Supercapacitor	Battery Storage
Investment (p.u.)	1	3–7
Footprint (p.u.)	1	7–10

Integrating supercapacitors into the STATCOM's DC link enables these devices to supply both reactive and active power, providing various grid-stabilizing services, including voltage regulation, inertia contribution, short circuit contribution, and system strength enhancement. These advanced devices are mature technologies already available in the market [23–29]. They enable the integration of two grid-stabilizing technologies into a single device, facilitating the integration of more renewable energy into transmission systems.

Drawing upon the E-STATCOM in [23,25] as a reference, this solution allows us to combine the following:

- STATCOM with power electronics-based modular multilevel converter with cascaded IGBT H-bridges—employed for supplying reactive power (voltage support);
- SCESS—utilized for injecting/absorbing active power to provide frequency support.

The combination of these two devices unlocks the operation in all four quadrants, proving both inductive and capacitive reactive power and, simultaneously, exchange active power in both directions with the network. A conceptual diagram of this system is shown in Figure 11, where supercapacitors are connected to the converter by the DC link. The voltage of the DC link must be sufficiently high to provide the correct amount of active power in the required time range. For this reason, most of the time, the DC side voltage is at medium voltage level, since the supercapacitors can be connected in series.

The power converter is based on a full-bridge MMC module, which serves as an interface between the AC network (PM1 referring to Figure 12) and another MMC full-bridge module adopted as a medium voltage DC/DC converter (PM2). The supercapacitor is linked to the right side of the PM2 converter through a couple of inductors, to dampen the high current discontinuities. The same topology can also be derived by means of an MMC half-bridge converter. Nevertheless, the full-bridge power module allows for better management of the supercapacitor operation and better optimization of the inductances.

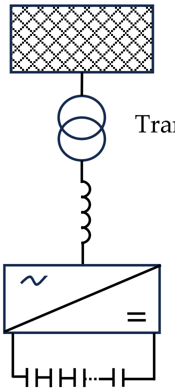

Figure 11. Schematic diagram of an E-STATCOM.

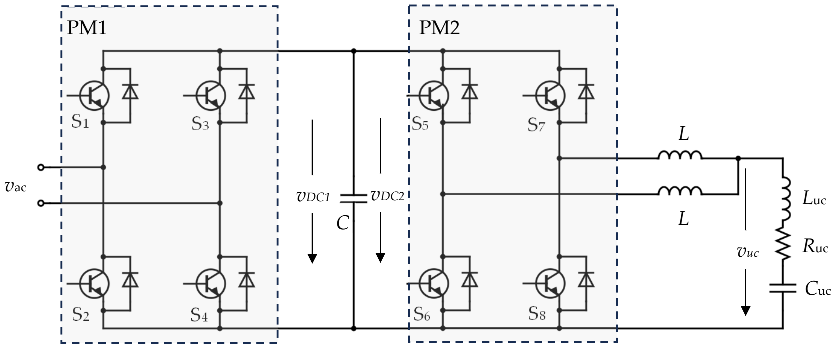

Figure 12. Scheme of the E-STATCOM topology with MMC power modules.

In Figure 13, an example of a station layout for a 50 MW system is presented. The E-STATCOM is installed in a converter hall and in a storage hall with the supercapacitors. Key specifications of the E-STATCOM in [23] (SVC PLUS FS by Siemens AG, Germany) are as follows:

- Footprint: approx. 2700 m^2;
- Active power: P_{max} = +/−50 MW;
- Reactive power: Q = +/−70 MVAR;
- $f_{deadband}$ = 0.2 Hz;
- Typical frequency deviation range: 0.5 Hz to 1.5 Hz, triggering the ROCOF control mode where the SVC PLUS FS injects or absorbs maximum power from the grid.
- Reaction time: typically 200 ms for measuring time, calculation time and acting time.

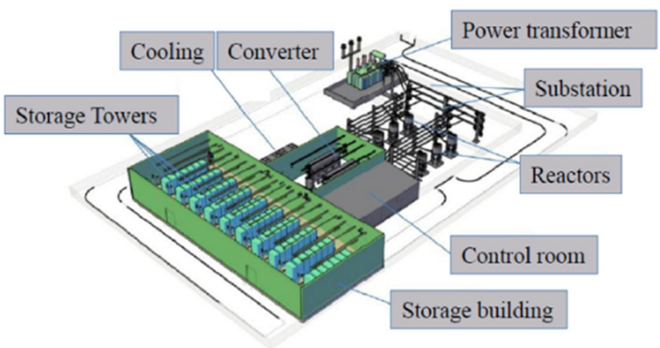

Figure 13. Typical station layout of an E-STATCOM. Reprinted with permission from [26].

The control system of the SVC PLUS FS is very flexible. It exploits the d-q rotating frame to enable independent control of the active and reactive power. This flexibility allows for adjustment according to the grid characteristics. Figure 14 illustrates a comparison between the SVC PLUS FS and various solutions for frequency support and inertia provision. These comparisons are based on simulations conducted using a model of the All-Irish Island power transmission system, which represents the synchronous operation of the Republic of Ireland and Northern Ireland [26].

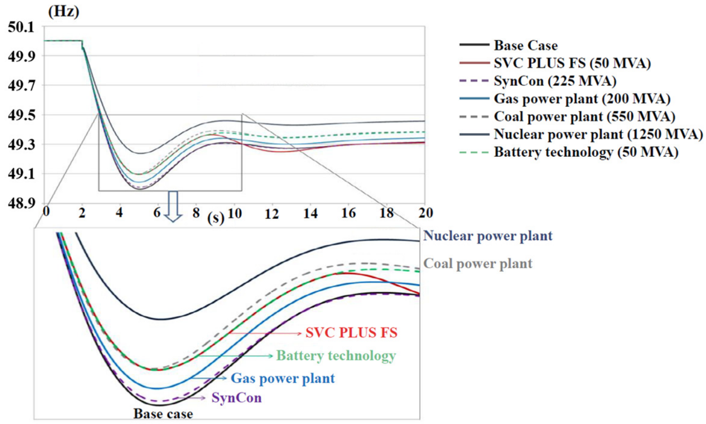

Figure 14. Impact of different solutions to improve the system inertia following a frequency imbalance. Reprinted with permission from [26].

Synthetic inertia solutions such as SVC PLUS FS and battery storage are controlled devices capable of providing grid support within the 5–10 s timeframe required for the primary response. These technologies can inject their rated power into the grid for short durations, effectively improving both the measured Rate of Change of Frequency (ROCOF) and maintaining minimum frequency within specified limits. Moreover, the impact of a 50 MVA SVC PLUS FS or battery storage is comparable to that of a large coal power plant.

STATCOMs equipped with supercapacitors (E-STATCOMs) offer several advantages that make them highly attractive for various applications. These include full-power availability, relatively low investment costs, and a favorable CO_2 balance. Compared to batteries, the SCESS system has the additional benefits of lower initial costs and a much smaller physical footprint when used for applications requiring fast frequency response within a range of several seconds.

4. HVDC Interconnection Improvement with FACTS

HVDC is a crucial technology for integrating RES into today's power systems [30–33]. However, as RES development leads to a reduction in conventional thermoelectric power plants, it can compromise the safe operation of Line-Commutated Converter (LCC)-HVDC systems, particularly during inverter operation, due to decreased short circuit power in the AC network. Moreover, commutation failures of LCC-HVDC could lead to dangerous values of ROCOF, which can potentially exceed the value of 2.5 Hz/s, i.e., the maximum allowable ROCOF value tolerated by HVDC systems, RES and energy storage systems.

Commutation failures (CFs) interrupt power transfer temporarily and cause significant overcurrent in the converter, impacting the AC system and placing additional stress on the LCC-HVDC system. Therefore, it is crucial to carefully evaluate CFs during the planning phase of the link by enhancing control systems and employing fast-acting voltage support devices like synchronous condensers or STATCOM. CFs are typically triggered by AC voltage dips at the inverter station, making LCC-HVDC connections to weak AC systems more susceptible to voltage fluctuations during both normal and emergency operations.

CFs normally happen on the inverter station of an LCC-HVDC system because the extinction angle of the thyristors is considerably lower at the inverter side than at the rectifier side [34,35].

The basic module of an LCC-HVDC inverter side system, whose layout is illustrated in Figure 15, relies on the thyristor valve-based three-phase full-wave bridge.

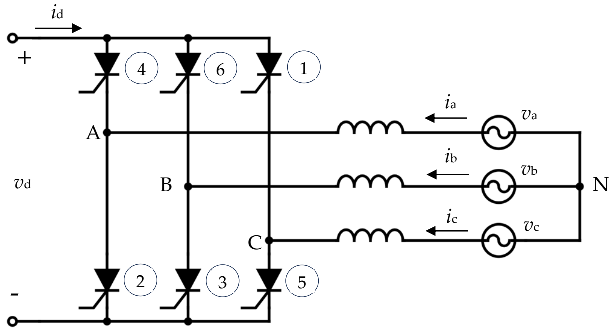

Figure 15. Basic scheme of an LCC-HVDC inverter-side system.

Figure 16 shows the DC voltage waveforms and the valve conduction periods of the full-wave bridge, where α denotes the ignition delay angle, β features the ignition advance angle, μ denotes the overlap, and γ represents the extinction advance angle.

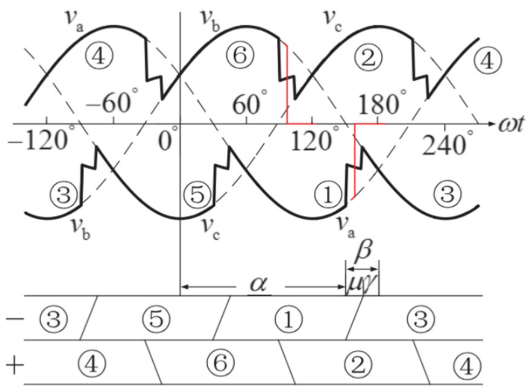

Figure 16. DC voltage waveforms shapes and valve conduction periods of an LCC-HVDC inverter system-station, with commutation failures highlighted in red.

The commutation refers to current flowing from one valve to another in the same bridge row. Commutation can be successfully executed in the situation, in which the changeover from the outgoing valve to the incoming valve is completely realized before the commutating voltage becomes negative. CFs may occur due to increased direct current, delayed ignition, or low AC voltage; direct current and ignition of valves can be regulated in most cases, while CFs caused by low AC voltage have not been practically addressed and effectively controlled.

Considering, for example, the commutation from valve 1 to valve 3, starting from ωt = α (Figure 16), there exists an overlap angle μ and the commutation is finished at ωt = α + μ, because of the impact of the inductance L_c of the AC source. Due to valve deionization, a minimum extinction advance angle limit γ_{min} emerges on γ. For this reason, a potential magnitude reduction or a waveform distortion of v_a, leading to a commutation voltage v_{ba} negative for $\omega t \in$ [α, α + μ + γ_{min}], as spotted in red in Figure 16, may result in a CF of valve 1. Considering the upper row valves and the commutation from valve 6 to valve 2, for example, the magnitude reduction or the waveform distortion of v_b leading to a commutation voltage v_{cb} positive, may bring about a CF of valve 6, as highlighted in red in Figure 16. In this sense, those disturbances that lead to the commutation voltage negative for lower row valves or positive for upper row valves may bring about CFs on the inverter system.

The effective operation of LCC-HVDC in a power system is strictly correlated with the AC network strength [36]. The AC network strength, for the connection of an LCC-HVDC system, is quantified by a parameter named the short circuit ratio (SCR), that, as reported in (12), can be calculated as the ratio of the short circuit level, SCL, at the connection busbar to the DC power capacity (rating) of the LCC-HVDC system, P_{DC}:

$$SCR = \frac{SCL}{P_{DC}} \tag{12}$$

Typically, a strong network system has an SCR higher than 3. To ensure the safety operation of an LCC-HVDC system, a minimum SCR of 2 is generally required, even if an $SCR > 3$ is preferred. SCR indicates whether an AC network can be impacted by a fault and how it affects the commutation voltage of the LCC-HVDC converter. A major disturbance of the AC voltage waveform, such as a heavy short circuit near the converter, can lead to a commutation failure. Systems with higher levels of SCR experience smaller or limited disturbances for a given fault impedance, thus reducing vulnerability to CF as SCR increases.

The Commutation Failure Immunity Index ($CFII$) characterizes the robustness of an LCC-HVDC system connected to an AC network of a specific strength. $CFII$ is determined by identifying the critical fault level at the inverter Point of Common Coupling (PCC), which can cause a commutation failure. $CFII$ is defined by the following formula [35]:

$$CFII = \frac{Critical\ Fault\ MVA}{P_{DC}} \cdot 100 = \frac{V_{AC}^2}{\omega L_{min} P_{DC}} \cdot 100 \tag{13}$$

where L_{min} is the lowest inductive impedance related to the most critical fault that can be supplied by the converter. Thus, $CFII$ represents the maximum fault level that does not induce a CF, expressed as a percentage of the HVDC rated power. A standard STATCOM connected at the PCC at the inverter terminal of an LCC-HVDC link can enhance the robustness of the system against AC voltage disturbances that might otherwise cause commutation failures. Considering an LCC-HVDC link based on the 1000 MW CIGRE benchmark system, Figure 17 illustrates the $CFII$ improvement achieved with STATCOM.

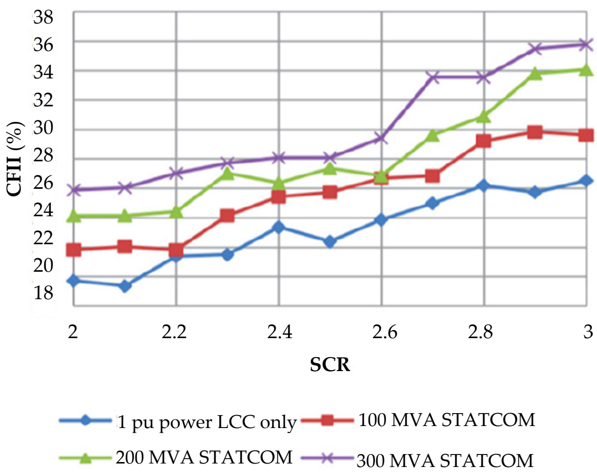

Figure 17. CFII improvement for an LCC-HVDC system equipped with a STATCOM. Reprinted with permission from [35].

The analysis on the $CFII$ improvement due to a STATCOM connection was carried out by opportunely modeling and studying the LCC-HVDC system (Figure 18) and the consequences of a fault after a steady-state situation. This investigation was reiterated for different fault impedance levels to establish the lowest fault impedance value that would not lead to a CF.

This analysis was reiterated for network strengths for SCR levels from 2 to 3 in increments of 0.1. The smooth and fast voltage control offered by STATCOM is able to importantly improve the $CFII$ of the LCC-HVDC system equipped with a STATCOM. With higher STATCOM ratings, the CFII improvement evidently emerges more and more

(Figure 17) because of the enhanced voltage support from an increased reactive power compensation. SCs can also mitigate CFs, as reported in previous studies [12,13,30]. Despite these improvements, CFs can still occur, potentially leading to interconnection outages and significant power imbalances, causing high ROCOF values and under- or over-frequency deviations (depending on the sign of the power outage). The mitigation of this phenomenon is possible by using innovative technologies like E-STATCOM [29]. Depending on the power flow of the interconnector, the state of charge (SOC) of the E-STATCOM can be adjusted. When exporting power, the E-STATCOM should be able to absorb power from the grid temporarily during an interconnector outage. Conversely, when importing power, it should inject power into the grid during an interconnector outage.

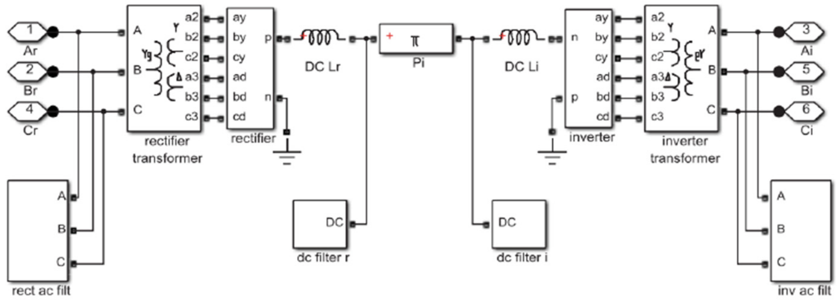

Figure 18. Schematization of the LCC-HVDC model used for the CFII study and based on CIGRE Benchmark [35].

5. Key Applications in Europe

5.1. SC/SCF in Italy

Given the rapid change of paradigm with RES units increasingly replacing thermoelectric plants for power generation, the Italian TSO Terna, as an important move, decided to install synchronous condensers in different crucial nodes of its transmission network. The aim was to support the system and provide it with the needed reactive and short circuit power as well as inertia level. The first synchronous condensers were installed in Sardinia (two in Codrongianos, in 2014) and in Sicily (in Favara and in Partinico, in 2016); these first solutions were without flywheels. Starting from 2020, the new synchronous condensers installed in Italy have been coupled by loss optimized flywheels to extensively increase the level of inertia provided to help stabilize the network frequency. Figure 19 displays a map of SC/SCF (with each device rated 250 Mvar) that have been or are being installed in the Italian transmission grid [37,38].

Figure 19. Map of SC/SCF installations in Italian transmission network [37,38].

5.2. STATCOMs 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 [37].

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 for the HVDC interconnection between Italy and Montenegro (MONITA); Latina, terminal for the HVDC link between mainland Italy and Sardinia (SAPEI); Galatina, terminal for the HVDC tie between Italy and Greece (GRITA).

In 2023, an additional two STATCOMs (rated ±125 Mvar each as well) were further installed and implemented in Aurelia and Montalto nodes (in Latium region), for a total of five STATCOMs so far. Figure 20 maps the installation locations of the five STATCOMs in the Italian transmission system [38].

Figure 20. Localization of the five STATCOMs in the Italian transmission grid [38].

Table 3 reports the key figures of these installed devices; all of them are connected at the 380 kV level.

Table 3. Key data of STATCOMs installed in the Italian transmission grid.

Node/Substation	Zone	Voltage	Rating
Villanova	Centre	380 kV	±125 Mvar
Latina	Centre	380 kV	±125 Mvar
Galatina	South	380 kV	±125 Mvar
Aurelia	Centre	380 kV	±125 Mvar
Montalto	Centre	380 kV	±125 Mvar

In comparison with an equivalent rating SC/SCF, a STATCOM may need a higher footprint level. For this reason, STATCOM devices are often installed as space-saving containerized solutions. The key advantage of these technologies lies in their dynamic features and response speed. 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).

It is important to mention that, in Italy, more projects and plans for installation of STATCOMs at the distribution level (so-called D-STATCOMs) are ongoing; one of the most advanced initiatives concerns the distribution grid expansion plan of the DSO (Distribution System Operator) of Milan's city area, Unareti, in which three ±50 Mvar-rated STATCOMs are due to be commissioned at the 23 kV level by 2025. Each of the three STATCOMs is to be installed in a 220 kV/23 kV primary substation through a dedicated 63 MVA transformer [39,40].

Finally, at the industrial level and the non-utility level, more STATCOMs have recently been installed in Italy, especially in the steel sector, towards voltage stabilization.

5.3. STATCOMs in Europe

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. 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. At the transmission level, most STATCOMs in Europe have been installed over the years in the 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 realized 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 [41].

More recently, the 1.2 GW Hornsea ONE offshore windfarm installation in the UK North Sea, completed in 2020, features 3x ± 200 Mvar STATCOMs [42]. 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. 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) [43].

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 [44,45].

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 ten STATCOMs by 2030 [46,47]. 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. 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 [46].

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 [48]. These four STATCOMs in Amprion's system are due to be completed and put in operation by 2024. 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 RESs [49].

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. 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 [46]. 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). 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 [46,50].

The demand for STATCOMs in Europe is constantly increasing, not only at the transmission and distribution level from grid operators and RES stakeholders but also in the steel sector as a result of different national and regional infrastructure development support plans [48].

5.4. Hybrid Synchronous Compensator

As seen, SCs and STATCOMs offer complementary benefits, making it possible to combine them in a way that maximizes their strengths while mitigating each other's weaknesses. In [51], the installation of SC and STATCOM at the same PCC is described and reported as a Hybrid Synchronous Compensator (H-SC) (for Phoenix project). Figure 21 illustrates a simplified diagram representing a standard H-SC setup.

In Figure 21, the H-SC is made up of an SC section and a STATCOM section, which are connected to the high-voltage (HV) grid's point of common coupling (PCC) through a three-winding, three-phase transformer. Multiple SC or STATCOM sections can be connected in parallel if required.

The technologies of SC and STATCOM are generally equipped with stand-alone control systems. In an H-SC setup, though, the stable functioning of the two control systems at the same time necessitates coordination. Therefore, a Master Control is designated to oversee the coordination, with the specific purpose of monitoring, synchronizing, and optimizing the concurrent operation of the STATCOM and SC control systems. Master Control prevents "control hunting" between the two systems and ensures that the combined branches operate efficiently as a unified system.

The Master Control includes various objective functions to fulfill its purpose. Some of these are optimization-based, while others serve as coordination functions, control strategies, or calculation tasks. Typical functions of Master Control include the following:

(1) Coordinated Management of Voltage and Sharing of Reactive Power, (2) Minimization of Power Losses, and (3) Compensation for Fast Transients [51].

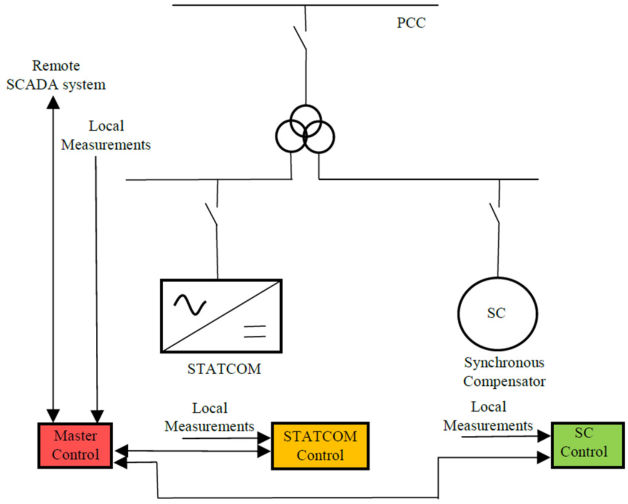

Figure 21. Schematic single-line diagram of an H-SC setup (reprinted with permission from [51]).

6. Techno-Economic Overview

6.1. Costs

As for all technologies, different cost components must be considered for STATCOMs. The main categories of cost components refer to raw materials, manufacturing and labor.

Manufacturing expenses include several items, such as depreciation costs for the equipment, plants, manpower accommodation places and warehouses, and expenditures for energy consumption, as well as costs for manpower safety and health, maintenance and spare parts, small value, other material expenses, etc. The contribution of raw materials to the final cost of the product is heavily dependent on the component price.

Overall, the cost of raw materials plays the main role; this component contributes to ca. 70% of the whole cost, whereas the expenses for manufacturing and labor amount to ca. 20% and 10% of the total cost for a STATCOM, respectively.

Concerning the overall costs for STATCOMs, in comparison with other technologies, Figure 22 provides an updated outlook [42]. As can be noticed, STATCOMs are more expensive than capacitor banks and SVCs, as expected, but they are more convenient than synchronous condensers. Typical cost ranges for STATCOMs are between 40 k€/Mvar and 150 k€/Mvar. These cost ranges are confirmed by recent STATCOM projects commissioned in Italy, Germany, and the UK; local situations may impact the final price.

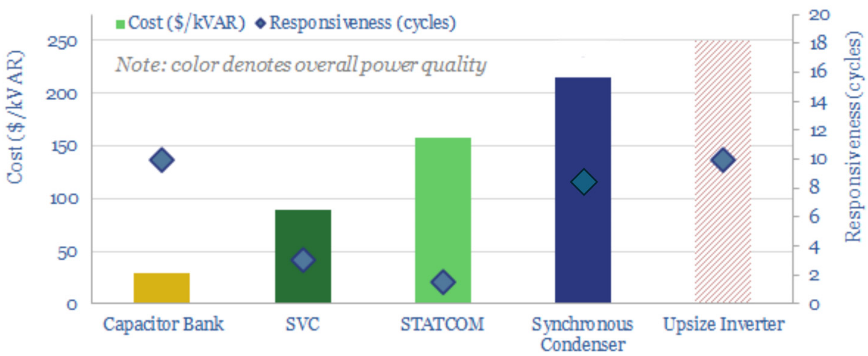

Figure 22. Comparison of costs and responsiveness for different technologies (modified/updated from [42]).

Figure 22 also reports a comparison of technologies in terms of their responsiveness. As can be seen, STATCOM control is confirmed to be featured with faster response characteristics [42].

6.2. Reliability/Availability

Concerning reliability and scheduled/forced unavailability, while data and survey outcomes are generally available regarding SVCs, statistics and data for STATCOMs are still rather scarce in the public domain. In [52], the outcomes of surveys conducted in 2017 and in 2019 across several countries/systems are reported. Regarding SVCs, from a 2017 survey (based on 2015–2016 performances), it emerged that, with the exception of a few systems surveyed, the average Forced Outage Unavailability (FOU) of SVCs was less than 1%. Furthermore, based on the information in the survey, auxiliary systems and the AC equipment technologies are the most vulnerable elements that mainly contribute to the forced outages. On the other hand, the outages caused by the switching equipment (for TCR or TSC) and controls are rather limited. The 2019 survey reported in [52], that looks back at 2017–2018 performances, includes more elements on STATCOMs as well, focusing on 42 SVCs and 12 STATCOMs worldwide; it provides average levels of FOU for the aggregated set of systems amounting to 0.87% (for 2017), 0.27% (for 2018), and 1.21% (for the combined period). From the survey, it emerges that 67% of the outages are attributed to auxiliary systems alone (not including the AC switching equipment). AC equipment, auxiliary systems, and AC filters as well as control and protection systems have been the weak points in some outage cases. This is also reflected in terms of outage duration [52].

As for SVCs, existing aggregate failure data revealed high system availability in practical STATCOM installations, approaching, in most cases, 99%, with a converter reliability of about 99%. Partial and even full redundancy of critical STATCOM components is commonly offered by manufacturers. This fact can explain the high availability exhibited by the system in practice.

In [53], the use of failure data for the STATCOM system main components, obtained from alternative installation types, was considered to fill the information gap. Reliability analyses conducted with a purpose-built analytical model and the calculated reliability indices revealed a theorical STATCOM availability of 99.75%, which aligns with empirical evidence.

7. Final Comparison

Table 4 presents a summarized comparison of the technologies presented in this review. The different features of the compared technologies can be appreciated in relative terms (by the use of +/++/+++ to rank them). An important trade-off between STATCOM/E-STATCOM and SC/SCF can be performed, at least in qualitative terms. Apart from the overload capability, the E-STATCOM is the most performant option, with a more convenient cost with respect to SC/SCF.

Table 4. Summarized comparison of the different technologies analyzed in this review.

Grid Stabilizing Service	SVC	STATCOM	SC	SCF	E-STATCOM
Voltage regulation	Yes (++)	Yes (+++)	Yes (++)	Yes (++)	Yes (+++)
Inertia	No	Negligible	Yes (+++)	Yes (+++)	Yes (+++)
H(s)	/	~0.01–0.02 if CMI	~1.25–2	7	8
Short circuit contribution	No	No	Yes (+++)	Yes (+++)	Yes (++)
Modularity	No	Yes (++)	No	No	Yes (++)
Controllability	Low	Medium	Low	Low	High
Operating regions	Asymmetric	Symmetric	Asymmetric	Asymmetric	Symmetric
Overload capability	Limited by time and amount	Limited by time and amount	Very good capacitive overload	Very good capacitive overload	Limited by time and amount

Additional elements for a comparison between E-STATCOM and SC/SCF could play a role in case a decision has to be taken by network planners and operators (TSOs), considering parameters, such as power losses, footprint, lifetime, maintenance need, and availability. In terms of power losses, SCF represents a less efficient solution due to the significant impact of mechanical friction in machines and flywheels, with copper loss in coil. On the other hand, in E-STATCOM, power losses mostly regard and depend on components, like converters, transformers and auxiliaries, and at the minor level on the supercapacitor (for less than 10% of the total losses for a 100 MVA E-STATCOM at no load conditions) [22].

Regarding footprint, SC/SCF solutions can be compact and provide inertia response. For an E-STATCOM, the footprint must consider the impact of the supercapacitor together with the valve room. In this sense, an E-STATCOM may be disadvantaged with respect to SC/SCF. It also depends on the device design. It must be highlighted that at equal rating and inertia constants, an E-STATCOM can be more efficient than SC/SCF in terms of effective energy. Looking at the device lifetime, SC/SCF technologies, featuring the absence of capacity degradation, are, in theory, able to be in line with TSO requirements for up to 40-year operation duration. In contrast, the storage technologies in E-STATCOM are generally to be completely replaced after 10 to 20 years of operation, depending on technical and environmental requirements.

Concerning operational needs, SC/SCF devices are more frequently subjected to maintenance because of their rotating parts. Also, SC/SCF options have lower availability in comparison with E-STATCOM technologies. Moreover, given their modularity, E-STATCOM options can further increase their reliability and availability by adding redundancy, i.e., more valve cells and supercapacitor modules/racks. Furthermore, an E-STATCOM, in case of outages, can operate at reduced power and energy ratings, with a limited number of units functioning, and it can disconnect the SCESS system from the MMC, operating as a classic STATCOM [22].

8. Conclusions

This review targeted the evaluation of the ongoing evolution of FACTS devices to compare them with conventional devices, towards the enhancement of power system stability in terms of the following:

- System inertia improvement;
- Frequency stability;
- Voltage stability.

Several recent FACTS technologies have been compared and discussed. This review focuses on the synergy between different technologies and shows that they can effectively achieve the objectives of power system stability, especially for the enhancement of system inertia. The respective combination of SC with flywheels and of STATCOMs with SCESS (E-STATCOMs) has the capability to reduce the Rate of Change of Frequency (ROCOF) and increase the nadir in various studies reviewed in the literature.

Another interesting consideration raised from this review is how some technologies analyzed, such as STATCOM and E-STATCOMs, can support LCC-HVDC systems. If an LCC-HVDC thyristor commutation fails, the STATCOM/E-STATCOM can absorb or inject power into the grid, thereby stabilizing the frequency.

A promising synergy analyzed is the combination of SCs and STATCOMs; these complementary technologies can leverage their individual strengths and compensate for their weaknesses. The combination of a synchronous condenser and STATCOM at the same PCC is known as a Hybrid Synchronous Compensator (H-SC).

The overview of the new projects and installations in Italy and Europe shows that these types of synergies are increasingly being adopted by the TSOs to provide multiple network services with a single device. The economic analysis shows that, despite STATCOMs exhibiting higher costs (only SCs are more expensive), their high responsiveness makes them competitive with other technologies such as SVCs, which are less responsive.

Concerning reliability and unavailability, while data and survey outcomes are generally available regarding SVCs, statistics and data for STATCOMs are still rather scarce in the public domain. However, some recent studies show that the level of FOU for STATCOM devices remains generally below 1%, as for SVCs.

Finally, it is worth mentioning that for the different grid-stabilizing services, the comparison of an E-STATCOM with SC/SCF provided interesting outcomes in favor of an E-STATCOM solution. However, depending on the specific application and design features as well as local technical and environmental conditions, network planners and operators (TSOs) will have to select the most suitable solution.

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