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Review

VSC-HVDC and Its Applications for Black Start Restoration Processes

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Abstract: System reliability is a measure of an electric grid system's ability to deliver uninterrupted service at the proper voltage and frequency. This property of the electric system is commonly affected by critical processes, such as a total blackout. The electric system restoration is a complex process which consists of returning generators, transmission system elements, and restoring load following an outage of the electric system. However, the absence of a generator or unit of black start capabilities may worsen the duration and effects of blackouts, having severe consequences. Black start capability is important as it can reduce the interruption time, decrease the economic loss, and restart the power supply fast and efficiently. In recent years, several works have reported advances about the High Voltage Direct Current (HVDC) technology based on the Voltage-Source Converter (VSC) as an attractive and promising technology to increase black start capability. This paper is a review of the current studies of VSC-HVDC as black start power and discusses the advantages and limitations of recent methods. The major points addressed in this paper are as follows: the current theoretical approach of the black start process and the used HVDC technologies, the advantages of VSC-HVDC as black start power, a compressive review of the literature about the black start capabilities using VSC-HVDC technologies, and a description of the main methods recently used to provide an enhancement for restoration processes. Finally, this paper discusses new challenges and perspectives for VSC-HVDC links in order to provide an enhancement for restoration processes.

Keywords: HVDC; VSC; black start; restoration processes; power grids

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1. Introduction

Over the last decades, technological development and research have aimed for the enhancement of the performance, robustness, and security of power grids, which have grown in size and complexity due to the inclusion of new sources of power generation [1] and recent trends in electricity markets [2]. This growth makes power grids more difficult to control [3], and makes them prone to succumb to power outages due to operational failures. Currently, the interest on the reduction of failures has been a priority of the utmost importance, as they cause interruptions of service to clients of the grid.

Operational failures can appear at any stage of power supply, from generation, passing through transmission, and up to distribution to consumers. Therefore, every element of the power grid is vulnerable to faults.

When a portion of an electric network goes out of service because of a power outage, this portion can be brought back online using top-down restorations with the aid of the surrounding elements of the grid [4], however, when the outage encompasses great portions of the network, power has to be brought back bottom-up [5].This kind of restoration is called black start and, as it is notably more complex and difficult than the other kind, efforts are constantly undertaken in order to develop new optimization schemes [6], performance evaluation methods [7], and alternative and innovating solutions that can provide modern power grids with increased robustness and security in this aspect.

Massive blackouts can have devastating consequences if they are not mitigated in a fast, efficient way, and, as we learned from the 2003 blackout in the USA and others [8], every possible action should be undertaken in order to mitigate their duration and effects.

Conventional black start schemes use generating units that can start by themselves (without the need of auxiliary power supply), some of which can be hydro, diesel, and gas units [9,10]. In microgrids, the black start schemes include energy storage systems (ESS) which lead with the issues generated by overcharge and over-discharge from the penetration of renewable energy sources or cyber-attacks [11,12]. In order to reduce the variability generated by the renewable energy and achieve a faster restoration of the black-start system, the ESS have been widely used [11–15]. Additionally, different strategies and schemes of control are used to improve the black-start system at smart grids for medium voltage levels. The strategies of control used during the black start requires maintain system frequency stability, system balance, and even facing the unavailability of communication networks [14,15]. In both schemes, the restoration of power back to the system is done in an orderly manner, supplying power from the black start unit to the rest of the grid, and can happen simultaneously in various parts [16] by separating the affected zones into islands that will later be synchronized, forming bigger and bigger portions of the grid until total restoration is reached. Nevertheless, as any proposal that can enhance and speed up this process should be explored [17]. Due to the importance of achieving an appropriate response in this kind of event, the use of other elements and equipment within the grid has been explored as a possible way to develop better black start schemes.

A great number of these proposals are based on the use of High Voltage Direct Current (HVDC) links, especially those working through Voltage-Source Converters (VSC) [18–22].

VSC-HVDC links, besides transmitting power over long distances, have a big potential for mitigating the adverse effects that faults have on grid performance, increasing a grid's flexibility, resilience, and robustness when they are present [23], as they provide reactive power support, AC voltage control [24], and frequency control [25] while "firewalling" one AC system so that disturbances do not spread to adjacent zones [26].

This paper explores promising proposals that use VSC-HVDC links for black starts, showing the diversity of literature and research that has recently showed how this technology can support grids through frequency, voltage support, control [27,28], transient behavior control [29], power oscillation damping [26,30], and soft-starting schemes [31]. All of the proposals included in this paper are proof of the huge potential that HVDC technologies have for achieving a superior performance on future power grids.

2. Black Start

A restoration of the grid is a process necessary after a power outage has been experienced. The outage can be small and involve only a portion of the grid, as it most commonly happens, relying on the assistance of other neighbour systems. As stated in [4], these blackouts require a top-down restoration, where the tie lines that link the affected system and the support system are energized for delivering power to the affected transmission network. From there, power is delivered to the pertinent systems for bringing local generation online.

Widespread power outages are a completely different story; a restoration after one of these events is far more complicated because it has to be done bottom-up, which means starting from generating units delivering power to other units in order to bring them back online to, as quickly as possible, restore the whole system. These kinds of system restorations are called black starts and, most commonly, they are composed of different recovery sequences that occur at the same time at different points of the grid in order to accelerate the process. When isolated parts of the grid are ready to be connected, they have to be synchronized to restore the original system.

The process of restoring the portion of a power grid that has been affected by a power outage to its operating conditions, without relying on any external support from the unaffected parts of the grid, is called a black start [4]. Generally, any element of a grid that has been forced out of service can be put back online with the aid of external sources of power, but a black start restoration is notoriously more complicated than a conventional top-down startup, as the affected grid has to start by its own means.

Black starts need generating units that can either start on their own or have the necessary systems for turning on their auxiliary loads (like motors, ventilating systems, pumps, etc.) [4]. These units are then used to supply power to adjacent distribution and transmission lines, and the transformers that are in between. Considering the outstanding characteristic of being able to start without off-site power, black start units mainly belong to four categories [9,10]:

- Hydroelectric units, which have fast response features.
- Diesel generators, which are useful, despite their small size, for supplying power for starting larger units.
- Aero-derivative gas turbine generators, thanks to their steep ramp rate, i.e., a fast increase in their power output.
- Larger gas turbines, even though they are not themselves capable of a black start, they can be coupled with diesel generators for this purpose.

If a power system is not properly prepared against major outages, i.e., through black start capability, a large-scale fault can have catastrophic consequences. Studies have determined the possibility that if a fault occurred on strategic power plants, a global blackout would be imminent [32]. Massive blackouts, which occur when a fault has huge repercussions on the grid, have happened almost annually worldwide for the last two decades. As a result, the need for innovative applications and technical improvements of power grids will further increase [33].

When a power system has several sources of black start that have already been identified and taking into account the behavior of the structure of the grid and its optimum conditions, the complete power network has to be divided into two or more subsystems for an independent recovery in this way, accelerating the restoring process until the network reaches synchronization after the delivery of stable power on each system after a period of time [34].

3. Black Start Process Schemes

As simple as it can be, a black start unit is in charge of delivering power to its step-up transformer, to the lines connecting it to the target generating unit, to the target's transformer, and to the unit itself [24]. With that said, working simultaneously through every available unit may reduce, by an appreciable amount, the duration of the interruption. The level of segmentation of the total area of the grid is limited by the availability of resources, the rigidity of the systems' interconnections, and the efficient coordination of its recovery process. Therefore, how to design an adequate partition scheme and a recovery route on each system poses a vital issue for the implementation of black start methods [35].

In general terms, to implement a black start scheme, three functional modules must be considered when planning, which are: formation, verification, and optimization of starting schemes [36].

- Formation module: The power system starts an automatic black start search process through the local power distribution. Power plants which are on standby mode are identified, together with possible start routes. Every possible start scheme is generated automatically, conforming a database of initial schemes.
- Verification module: With the start schemes already proposed, analysis and simulation through software tools is done for verifying every proposed scheme. This simulation also takes into account characteristics such as self-excitation of some units, commutation under no-load conditions, and low frequency check [37].
- Optimization module: Aiming for the best possible performance, an optimal startup scheme is selected from the proposed options (this is done using decision-making methods). The selection of the final startup scheme is very important, as it plays a crucial role on the system's performance.

In practice, the performance of any black start scheme may be affected by a multitude of factors that are subject to constraints, some of which include: generation constraints (matching generation with active and reactive load and losses), crew constraints (availability of trained crew and operators), time constraints (time period for bringing units back online and "minimum downtime" for each unit) and reserve constraints (spinning reserve availability in case of any loss of units) [5].

Given the multitude of performance indicators that are relevant for evaluating proposed black start schemes, power systems take into account those indicators that best reflect the advantages and disadvantages of the startup. The general object of a system restoration is to restore as much load as possible in the shortest period. Therefore, restoration time and available generation capacity have to be selected as priority evaluation criteria. The former reflects the speed with which the generation unit restarts operations, while the latter represents the generation capacity that each unit can provide to the system [35]. Hence, considering both of the previous criteria, these five performance indicators may be chosen for evaluating black start proposed schemes:

- Generation capacity of each unit, as it determines the amount of energy that can be supplied to the system when it starts [38].
- Actual conditions of each unit: These conditions are determined by the temperature of their turbine cylinder. As a function of said temperature, the conditions of a unit can be divided into five categories: ultra-cold, cold, warm, hot, and ultra-hot [39].
- The ramp rate of each unit: During the restoration stage, the most important loads have to be restored first. Indeed, the units with the best ramp rate should be started first, due to their ability of quickly increasing their output. An example is shown in Figure 1.
- Startup power needed for each unit: In the first stages of the restoration, only a few units can act as black start units, and their output power is limited. Consequently, units that require less startup power must be restored first [40,41].
- Operation commutation number: On black start processes, some units provide energy to the power system through restoration routes. The number of commutation operations has an impact on the system, like frequency power overcharge and commutation overcharge [42].

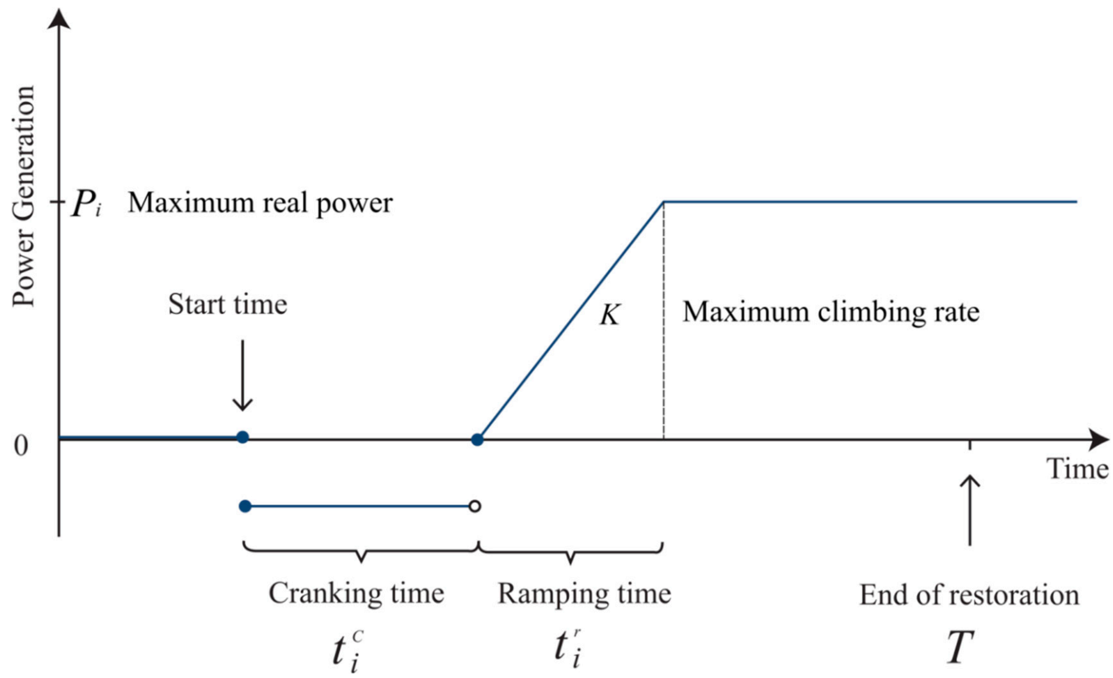

Figure 1. Ramp rate periods for a standard generating unit. The ramp rate is the increase of load that a generating unit can provide with respect to time.

4. Evaluating a Black Start Scheme's Performance

Quantifiable approaches which aim to build optimal partition and start-up sequence schemes have been proposed in [7,35,43]. In them, the performance of the proposed scheme is evaluated by taking into account the ramp rate of the black start units, the generation capability curve of the system, and its restoration efficiency, according to Equation (1).

$$f_1 = \frac{\sum_{i=1}^{N_G} b_i \int_{k\Delta t}^{T} P_{Gi}(t)dt + \sum_{i=1}^{N_{DC}} c_i \int_{k\Delta t}^{T} P_{DCi}(t)dt}{T} \tag{1}$$

where:

- f_1 is the efficiency of the black start scheme
- b_i is the restarting state indication of the unit G_i
- T is the total time consumption of units
- Δt is the time-stepping interval
- N_G are the units to be restored
- $P_{Gi}(t)$ is the MW output of the unit G_i
- N_{DC} is the number of HVDC converter stations to be restored
- c_i is the restarting state indication of the HVDC converter station DC_i
- $P_{DCi}(t)$ is the transmission power of the HVDC converter station DC_i

If G_i or DC_i are restarted in the kth time step, b_i and c_i, respectively, are 1; otherwise, they are 0.

From Equation (1) it can be assured that obtaining a faster increase on load capability and minimizing the time required for this process is the key for a successful restoration.

As shown in Figure 2, the behaviour of a black start scheme's increase in its possible power output can be modelled as a curve, which is very useful for analyzing its performance and comparing it to other proposals [43]. Typical generation capability curves have a resemblance to individual units' ramp rates, showing the initial cranking time of most of the units, the slope at their ramping stage, and the stabilization at the end of the restoration.

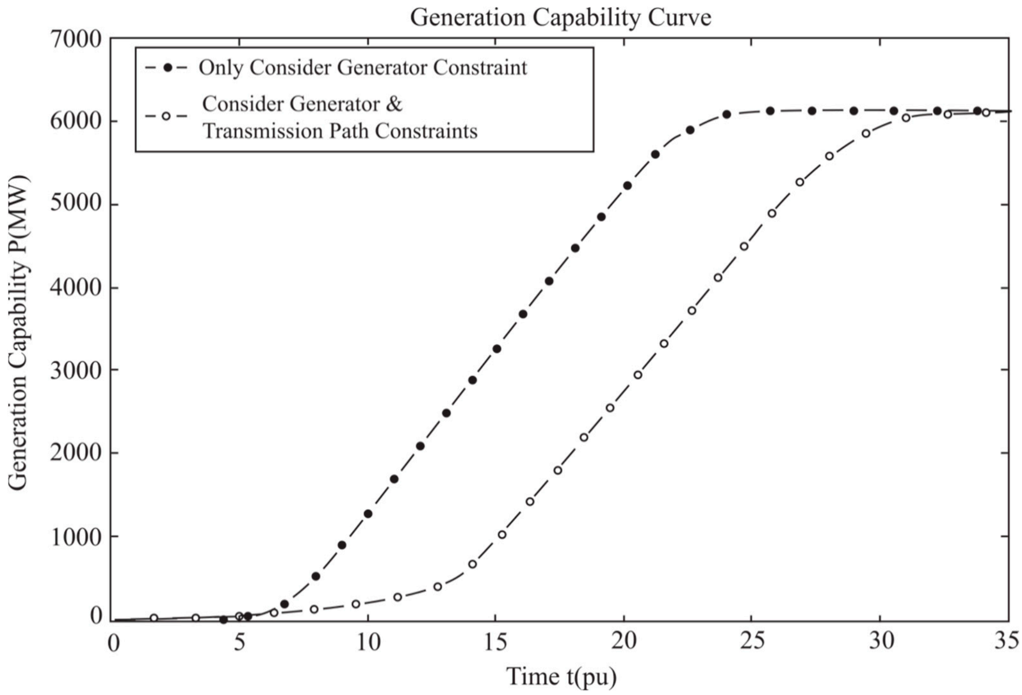

Figure 2. Generation capability curve. Graphic depictions of this kind ease the comparison of the effectiveness of different restoration schemes.

On a practical decision-making procedure of whether assisting or not during black start, there will always be uncertain factors. Since the 1980s, development and optimization of black start schemes have been explored in [7,35,43] and this continues as future power networks will demand a quicker and more accurate response to power outages. Thus, one of the most promising tools that can provide this performance enhancement is VSC-HVDC technology.

5. High Voltage Direct Current

The HVDC is a technology for transmitting electrical power in a safe and efficient way across large distances. It is suitable for specific applications such as interconnections, bulk power transmission, long-distance transmission via cable or overhead line, grid enforcement, multiterminal networks, and grid access for offshore applications. The first experimental trial for transmitting power in DC was developed in 1882, when Miesbach and Munich, in Germany, were connected through a 50 km long link with 2 kV DC lines [44].

5.1. HVDC Configurations

As shown in Figure 3, multiple arrangements can be achieved for HVDC links according to the number of conductors and their polarities. Some of which are monopole, bipole, and homopole configurations [45].

While the monopole configuration has poor availability due to relatively higher outages and homopole configurations are not frequently used because of the main disadvantage of presenting huge ground return currents, bipole configuration is used when power transfer capacity exceeds the monopole configuration or higher reliability is needed during the operation [46].

On the other hand, several configurations can be achieved with the arrangement of monopole or bipole configuration depending on its length, the number of terminals, and its purpose. These configurations are briefly described in Table 1, where, for long-distance land power transmission, bipole is a good choice as it can transmit 50% of its rated power during a fault on one of its poles. Bipole ground return topology is cheaper and more reliable than bipole with metallic return. Earth electrodes can also be used in bipolar HVDC systems, and they have very low current in nearly balanced pole voltages [46]. As having zero or almost zero ground current is an important advantage for a HVDC link, bipolar links are the most common arrangement [45].

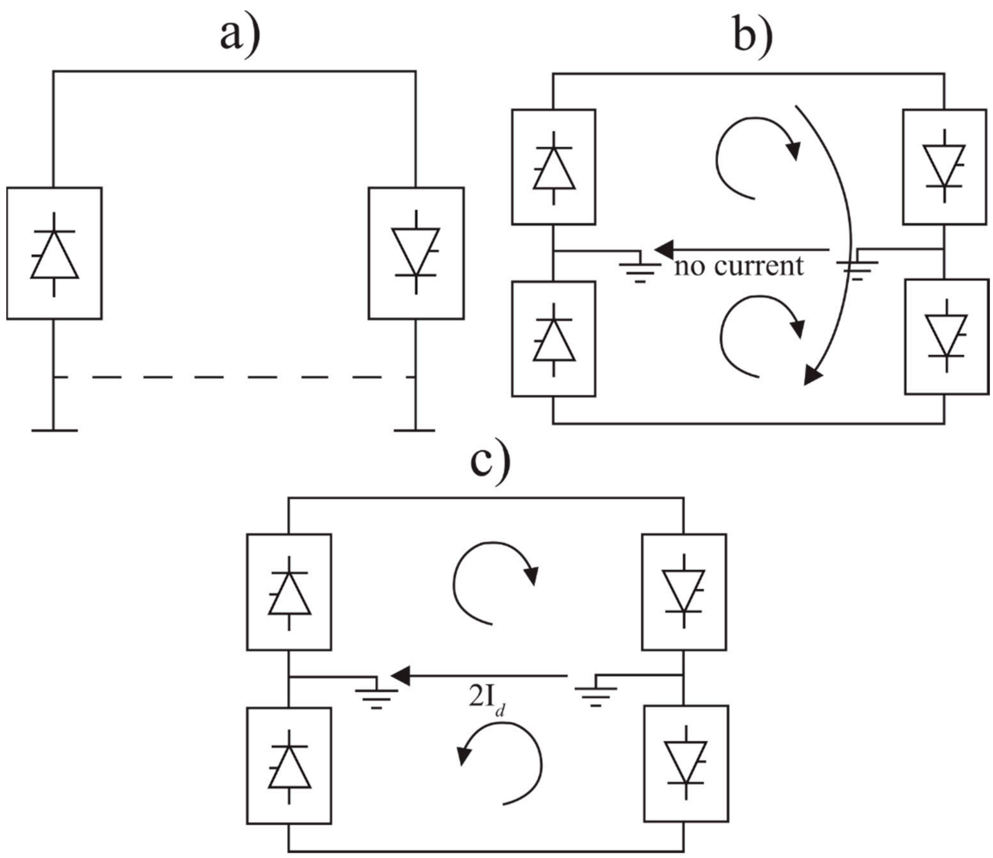

Figure 3. HVDC configurations: (**a**) Monopolar, (**b**) Bipolar, (**c**) Homopolar.

Table 1. Different configurations for HVDC systems.

Type	Description
Point to Point	Connection between two substations (point to point) when the HVDC alternative is better than HVAC. Each of the substations works as a rectifier or inverter, depending on the direction of the power flow. This is the most common type of HVDC link.
Back to Back	Connection of two different frequency systems inside a substation.
Multiterminal	Used when three or more substations are connected to a HVDC system.
Unitary	Used when the DC transmission is performed directly at the power generation point. Mainly used in hydroelectric or wind power plants.

5.2. HVDC Benefits

Since the first commercial HVDC project was completed between the Swedish island of Gotland and mainland Sweden in 1954 [47], this energy transmission technology has been increasingly used worldwide due to its operational and economic advantages over conventional AC transmission methods. Furthermore, a direct current transmission line serves the same purpose as its AC counterpart, with added capabilities that make it ideal for applications such as asynchronous interconnections between grids, underwater cables, long-distance power transmission, and stabilization of power flows [48]. Some operational and economic advantages can be listed as follows:

1. Operational advantages
    a. The power carrying capability of a DC line is unaffected by its length due to the capacitance phenomena in cable only appearing when the cable is energized for the first time or when the value of voltage changes.
    b. As a DC line requires no reactive power, controlling the voltage at both ends is easier.
    c. Their technology does not need voltage compensation to overcome problems, such as line charging and stability limitations.
    d. A DC line can interconnect two grids as an asynchronous link rather easily thanks to its fast controllability of power flow.
    e. Whereas AC lines cannot operate on unbalanced conditions for more than a second, bipolar DC lines can operate on single pole configuration for extended periods of time.
2. Economic advantages
    a. Right of Way (RoW) incorporates small towers in comparison with the towers used in AC transmission and requires less land for its installation, which translates into a reduction cost for the tower and its installation.
    b. DC lines can carry, with two conductors, as much power as an AC line using three conductors, which represents a reduction in cost for end users.
    c. The line cost is reduced since it considers less conductors and insulators per pole.
    d. As it has fewer conductors, power transmission losses along a DC line are inferior to those of an AC equivalent after a certain length, as shown in Figure 4.

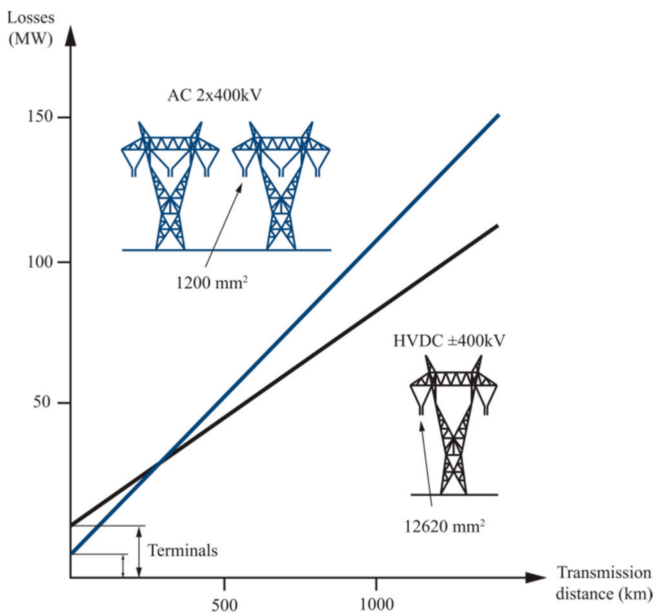

Figure 4. Power loss comparison between AC and DC lines.

6. HVDC Converters

The HVDC systems serve as a DC link between AC systems, where the connection needs to convert from AC to DC and vice versa. This process is done using converters, such as Line-Commutated Converters (LCC), Current-Source Converters (CSC), or Voltage-Source Converters (VSC).

Thanks to the development of new electronic devices such as GTO and IGBT in the 1990s, the use of VSC technology became fundamental in HVDC, mainly because of VSC's capability of providing secure commutation in an AC or DC system with the help of Pulse

Width Modulation (PWM). In that way, a VSC operating as an inverter can provide a sinusoidal output to the AC system [45].

Even though LCC systems are a mature technology that has been used for over 50 years in HVDC [49], Self-Commutated Converters have more advantages for mitigating issues related to low-inertia generation [30], which is increasingly being added to grids.

Of these Self-Commutated Converters—VSC and CSC—VSC is a more flexible technology since it allows for controlling active and reactive power independently [45]. Therefore, more advanced HVDC systems tend to use VSC-based technologies.

6.1. Operational Advantages of VSC

According to [45], VSCs have multiple advantages over both CSC and LCC, some related to their efficient operation and functioning principles, others associated with the compatibility of today's power electronics industry [49]. Some of these include:

1. Minimal environmental impact.
2. Ability to connect to weak AC networks and dead networks.
3. Rapid development in power electronics technology.
4. Ongoing development in the availability of various types of semiconductor switches.
5. Integration of renewable energy resources and storage systems in electric power grids.

Several PWM, and more advanced space-vector techniques suitable for VSCs, are described in detail in [27], which lead to a smooth operation capable of delivering alow-harmonic sinusoidal output to the AC-side of the system. This capability is more notorious in modern Modular Multi-Level VSC configurations, which are an emerging configuration in [27,50,51] with notorious technical and economic advantages [52].

Furthermore, the increasing use of VSC HDVC in smart-grids indicates that the role of power electronics in power systems is growing. Several power electronics experts have predicted that VSC-HVDC systems will probably replace thyristor-based systems, much like thyristors replaced mercury-arc systems [53].

It is important to mention that VSC can also modulate their valves to control reactive power, obtaining any desired power factor [45,54]. Therefore, VSC-HVDC links lend excellent voltage and frequency control for the AC grids connected to them.

6.2. System Restorations with VSC-HVDC

Even though VSC-HVDC technologies serve the main purpose of transmitting bulk power over great distances, several characteristics of their behavior make them excellent tools for participating in activities other than AC/DC power conversion and transmission [17]. VSC-based systems are able to feed networks with no local generation at the moment [55] and to control, in an easy and fast way, active and reactive power independently [56].

Justifying auxiliary purposes for increasing the development of VSC-HVDC technologies may boost their maturity, as any additional benefit that a HVDC link can deliver to the grid will increase its attractiveness and, therefore, will speed up the spread of this type of link on actual grids. The next section of this paper explores the ancillary services and support activities that a VSC-HVDC link, be it single or multi-terminal, can provide to the grid during restoration events.

7. Black Start Capabilities through HVDC

With further developments on renewable energy inclusion on electric grids, system operators have to look for efficient ways to provide a reliable and secure service to every user on these new low-inertia grids. One of the key aspects of this goal is to improve the overall robustness and controllability of electric systems, reducing both the frequency and the duration of unplanned events like blackouts.

This is exactly where HVDC-based technologies can support with ancillary services beyond those primarily intended for them (energy transmission). The inclusion of single and multi-terminal HVDC links on power grids, with appropriate control systems, can help to achieve a robust network that responds better than conventional AC grids to power outages.

The tools and advantages on which VSC-based HVDC systems can support in restoration events, due to their advantages over LCC in HVDC systems, include proposals that address issues like low-inertia mitigation and ease of control, and their increased use in today's electric grids. These ideas are summarized in the Table 2.

Table 2. Recent VSC solutions to HVDC Systems.

Paper	Problem	Solution	Results
[29]	Traditional VSC frequency control techniques are not appropriate for high harmonic distortion conditions.	A controller based on frequency self-adaptation tracking algorithm (FATA) is proposed for replacing Phase-Locked Loop (PLL) methods.	Better harmonic suppression, even for severe operating conditions, appropriate for both dynamic and steady state.
[26]	Conventional black start strategies require periodical tests to the equipment. Harmful phenomena related to transmission lines and transformers occur during abrupt start strategies.	This paper includes field test results of VSC HVDC performance as a black start source, with an overview of its control mechanisms and characteristics.	A comparison between traditional and VSC black start show that the latter offers reduced restoration time, safer and smoother restoration, and lower investment and maintenance costs.
[31]	Inrush currents and transient over-voltages can cause failure in a black start restoration.	Method for soft-energizing major power systems through VSC-HVDC.	No over-voltage or surge at all during the restoration.
[57]	Traditional black start problems such as: generator's self-excitation, switching surge and over-voltage while powering long no-load lines and ferromagnetic resonance while charging transformers.	Overview process similar to the previous paper, for using VSC HVDC terminals for soft starting transmission lines, later energizing assistance equipment for a generator and switching it on for restoring load.	This process, considering the changes of control modes of VSC and energization of auxiliary components, speeds up the restoration and proves VSC-HVDC an excellent black start source.
[58]	Traditional black start strategies are limited due to small power supply capacity, slow recovery process, slow recovery process, and weak power adjustment.	A method for supplying passive AC networks through VSC HVDC is proposed, using constant AC voltage control for enabling the system to operate normally under disturbance conditions.	Improved system stability during the recovery process, while also shortening the recovery time of the system.
[59]	System restorations on passive networks using Line Commutated Converter (LCC) HVDC is very hard. System restorations on passive networks using Line Commutated Converter (LCC) HVDC is very hard.	This paper explores the possibility to black start a passive AC grid without the need of telecommunication systems or external power electronics, controlling the AC voltage locally.	Through controlled capacitors, a successful method for providing black start capability with this alternate converter technology is presented.
[60]	Power oscillation, especially on weak or passive AC grids, adds to the difficulty of restoration processes.	Method for damping power oscillation both through active and reactive power supplied by VSC.	Transient stability and dynamic performance of power systems are considerably enhanced.
[61]	Transient stability of huge hybrid AC/DC systems is a great obstacle for their development.	Through independent P and Q injections from VSC, a method is proposed for increasing stability based on frequency deviations.	This method increases the ease with which a power system can be dynamically controlled.
[27]	Conventional grids are showing a decrease in their levels of inertia because of the replacement of conventional generators with low-carbon technologies.	A control method is proposed and tested for supplying the grid with fast frequency assistance, without risking the operation of the VSC.	A robust response to voltage and frequency drops is achieved, the designed scheme is autoregulated and enhances the transient performance of the grid safely.
[30]	Further inclusion of low-inertia generation on grids will make frequency control more challenging.	Method for providing frequency support for a system through the use of MMS VSC HVDC.	Significantly reduced spinning reserve requirements thanks to this alternative frequency support.

Table 2. *Cont.*

Paper	Problem	Solution	Results
[11]	In decentralized and independent control wind power and energy storage systems, the high variability generated by charging and discharging of energy storage produces an unbalanced system power which leads to the failure of black start.	A method based on a coordinated control strategy of multi-energy storage supporting blackstart based on dynamic power distribution divided into two layers is proposed to deal with the disorder of charging and discharge of energy storage.	The power balance and stable voltage frequency in black start of the power grid is carried out by a coordinated control strategy. At the same time, the adaptive dynamic distributions deal with the critical operation of overcharged and discharged energy storage systems.
[13]	Renewable energy cannot provide inertia response or frequency response as traditional synchronous generators; at lower inertia situations, the frequency changes faster.	A hierarchical predictive control method of wind farm with an energy storage system for frequency regulation.	In order to deal with the low and high wind conditions, two modes of control are implemented which are based on frequency regulation and reserve recovery mode.
[62]	The black start capability on conventional power plans is characterized by long start-up times due to their slow dynamics.	HVDC connected offshore wind power plants (OWPPs) provide fast and environmentally friendly solutions for power system restoration.	OWPPs can provide fast solution to power system restoration as long as the wind turbines are equipped with the black start capability.
[63]	Traditional case studies have been widely applied to two terminal hybrid systems which are used in a black start power provided by a single healthy AC grid.	The dynamic changes related to AC grid and converters are considered. In this sense, multi-terminal direct current systems facing the dynamic changes in a feasibility and effectiveness manner.	A new strategy based on an optimal power allocation to perform black start in the VSC based on multi-terminal direct current systems.
[64]	The faster recovery and controllability of black start capability during fault and maintenance.	A phase-locked loop (PLL) control scheme based on intelligent adaptable control to effectively achieve real power control is proposed.	An improvement in the black start rate of HVDC links.
[65]	The classical VSC-HVDC controller is load-dependent and has to be adjusted according to each operation condition.	A robust controller design that increases the robustness until operation conditions experience continuous variations.	A global stabilization and enhanced dynamic performance of the VSC-HVDC system.

Besides the content in the following tables, the proposals covered in depth in this paper show solutions to problems related to active power grids, unlike papers that explore VSC-HVDC assistance on the behaviour of passive grids. Thus, the solutions summarized are considered to be vanguard-technology control proposals with very promising expectations, whose main features would play a crucial role in critical restoration processes that require the best possible performance on precision and velocity of restoration, e.g., black start emergency schemes.

Beyond reducing the potential consequences of a power outage, if reaching the different target states proposed by a restoration scheme can be achieved more easily with these solutions while also increasing security and the speed of the process, further exploration and development in this field is crucial for black start studies.

7.1. Frequency Support through MMC-VSC Overload

While electric grids continue to include more and more asynchronous generation-like photovoltaic energy, system operators have to take into account that this poses a reduction in overall inertia, a phenomenon that increases the complexity of frequency control. In [30], a method is proposed for providing the grid with additional frequency support in case of emergencies through the use of Modular-Multilevel-Converter Voltage-Source Converters available in HVDC terminals, while keeping semiconductors within operational limits.

This method consists of allowing momentary overload capability to VSCs for acting outside their rated P/Q conditions through controlled circulating currents, allowing this capability to be used as a primary frequency response during unplanned events. Two alternatives are explored for this method:

1. Frequency-power droop controller, in which the converters' support is proportional to the frequency deviation, given by

$$P = K\Delta f(t) = K(f_0 - f(t)) \quad (2)$$

where:
P = Power response
K = Gain
$\Delta f(t)$ = Frequency deviation
f_0 = Nominal frequency
$f(t)$= Measured frequency

2. Maximum power release controller, in which the converter provides the maximum support available, expressed as follows:

$$P = P_{\max} - P_{rated} = 0.275 P_{rated} \quad (3)$$

where:
P = Power response
$P_{\max}$ = Maximum power support available
P_{rated} = Rated power output

7.2. Fast Frequency Support within Safe Limits

As well as the previous proposal, but without delving into the semiconductors' thermal performance, the authors of [27] aimed to mitigate the effects of low-inertia technologies being added to power grids. This scheme, however, does not contemplate an overload capability of the devices and, on the other hand, enhances the performance of the grid while staying within safety limits.

The proposed controller delivers extra active power through the VSC when needed. It generates a fundamental frequency waveform through the use of vector control. Consisting of two control loops, this cascaded controller has an external loop which aims to meet the system's performance requirements, while its inner loop is in charge of the protection and stability of the converters.

Figure 5 represents both loops of the controller and outputs i_{dref} and i_{qref} are used to regulate DC voltage (or active power) and AC voltage (or reactive power), respectively. The inner control loop has v_{dref} and v_{qref} as outputs, which are modulated voltage references for producing control signals.

The outer controller has two gains:

- K_f, which is the ratio between the maximum permissible DC voltage variation and the maximum drop expected in the frequency.
- $K_{V_{dc}}$, defined as the ratio between the extra active power that can still be delivered (difference between measured and nominal values) and the maximum permissible DC voltage variation.

Thus, the provision of this service by a converting station will not risk the integrity of the system. Some advantages worth mentioning for this scheme are (a) that power injection rises as frequency falls and the system reaches steady state at the same time as the frequency, and (b) this scheme prevents overloading AC transmission lines during load or abrupt generation variations.

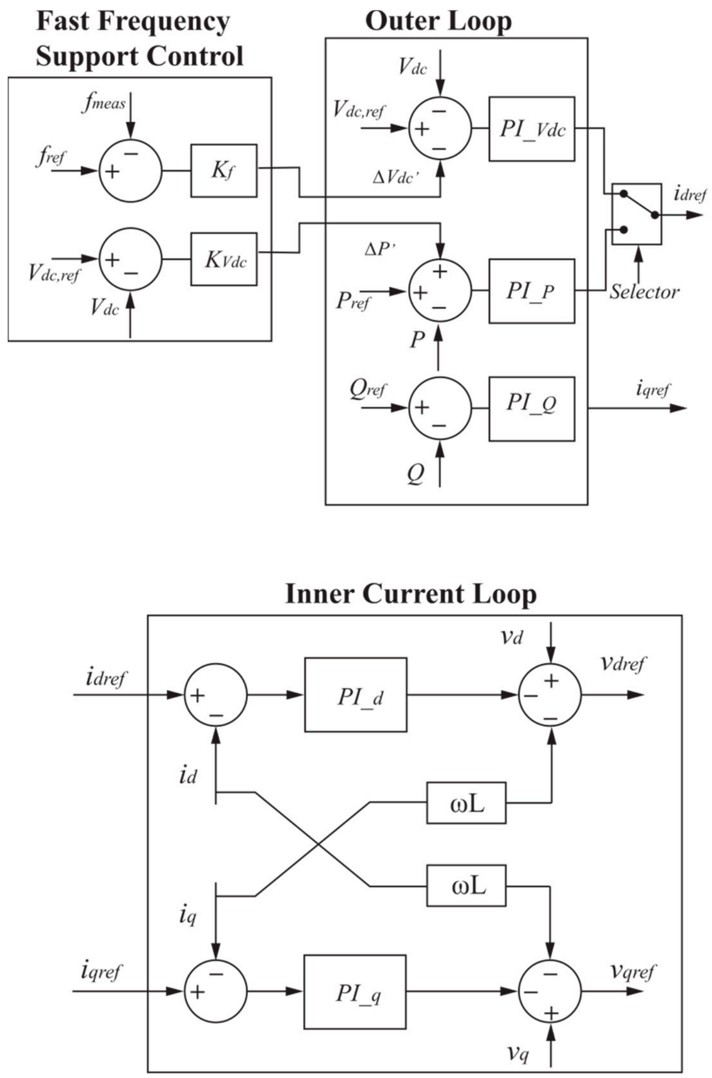

Figure 5. Cascade controller scheme for fast frequency support.

7.3. Transient Stability Improvement

Taking into account that every VSC in an HVDC system is able to independentlycontrol its reactive power injections, a method is proposed in [61] for increasing or decreasing the electromagnetic torque of the generators of a system in order to improve the system's overall stability. This is particularly important when thinking about the development of future projects consisting of huge hybrid AC/DC grids.

Besides controlling active power injections, the authors propose two different strategies for controlling reactive power injections in the system:

1. A global control method, using as a reference the weighted average of the frequencies measured on the terminals of the AC system. This set point is determined as:

$$W_i^* = \sum_{k=1}^{n} \alpha_k W_k \tag{4}$$

where:
W_i = Frequency reference
W_k = Frequency of the AC bus of converter K
$\alpha_k \in [0,1]$

In this strategy, each converter will inject, or consume, reactive power depending on whether its frequency is above or below the average.

2. A local frequency control strategy. Here, the Q injection of each converter is proportional to its local frequency deviation with respect to the nominal frequency of the system. This method reduces communication complications.

7.4. Power Oscillation Damping

As an additional function of MMC-VSC, a control scheme is proposed in [60] for damping the power oscillations of systems during emergencies. As in the previous proposal, the authors of this paper base their work on the independence between active and reactive power injections on a Voltage Source Converter.

The dynamic behavior of a power system can be further increased by the addition of this Power Oscillation Damping (POD) controller, aiding a recovery process even before it begins, as this type of controller is able to reduce the consequences of a momentaneous power outage while also maintaining the system within its security limits as it passes from one target state to the next one. The proposed POD controller consists of three elements: gain, washout, and lead-lag, as shown in Figure 6.

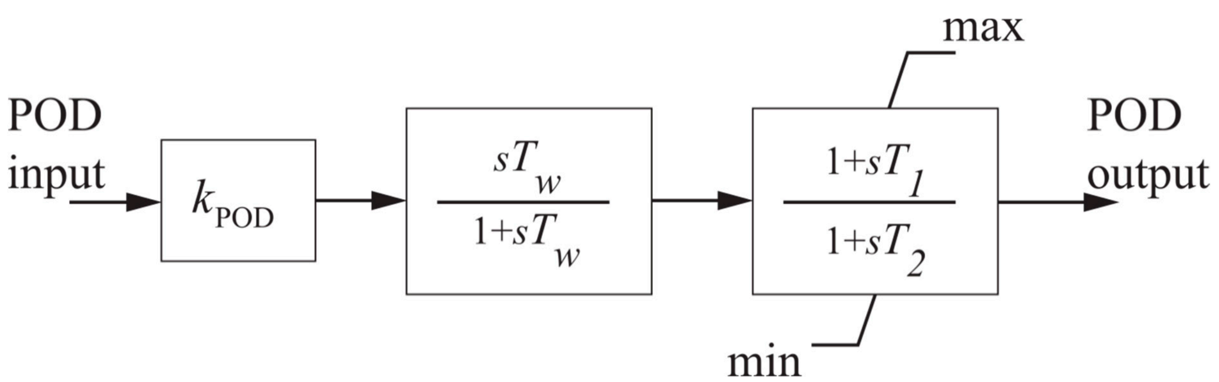

Figure 6. Transfer function of the proposed POD controller.

The input signal of the controller is the voltage angle at the bus of each VSC. It can be operated in order to modulate the active power injections or the reactive power injections. In both cases, this tool provides enhanced capability to improve the damping capacity of a system.

7.5. Power Oscillation Damping through MMC Overload Capability

In [66], the same authors of [30] developed a method consisting of the same momentaneous overload capability of MMC-based VSC for improving the grid's response against oscillations through the use of a POD as in the previous method, but including an analysis of the thermal dynamics in the semiconductors of the converter, further demonstrating its viability.

The short-term overload capability is a very promising scheme that allows up to 30% overload by limiting the peak currents present in the converter through the use of harmonic circulating currents. This implies higher losses from the semiconductors, but as the operation on overload capability is done only momentaneously, this disadvantage can be neglected.

Through the use of Model Predictive Control (MPC) theory, the developed POD regulates the transient behaviour of the grid during emergency conditions, having active power at the rectifier of the link as an input and the speed of the generators as an output. This solution is shown to reduce the adverse effects of power oscillation on simulations, enhancing the transient behaviour of the grid. The implementation of this kind of solution can allow a better use of conventional transmission infrastructure without exceeding its operational limits.

7.6. Soft-Start Capacity Using VSC-HVDC

During certain blackstart processes, abruptly switching on circuit breakers causes inrush currents and transient over-voltages, possibly causing failures in the restoration. For that reason, the method proposed in [31] explores the ability of VSC-HVDC systems for soft-energizing major power systems, avoiding the previous voltages.

With a method consisting of gradually increasing the AC bus voltage of the VSC adjacent to the affected grid and controlling the switching of certain circuit breakers on this ascending process, it is possible to achieve a restoration with no over-voltage or surge at all.

The ability to control the active and reactive power absorbed by the VSC independently is fundamental in allowing the black start facility to apply a soft energization method.

Consider P and Q as the active and reactive power absorbed by the VSC, respectively. From Equations (5) and (6) shown below, it can be concluded that P and Q can be controlled independently by δ and U_C. When a Pulse Width Modulation (PWM) is adopted, δ is the phase angle of the fundamental component of modulation wave and U_C is proportional to the modulation index M of the PWM:

$$P = \frac{U_s U_c}{X} \sin(\delta) \tag{5}$$

$$Q = \frac{U_s (U_s - U_c \cos(\delta))}{X} \tag{6}$$

$$U_c = \frac{M}{\sqrt{2}} U_d \tag{7}$$

where:

P, Q = Active and reactive power absorbed
U_s = AC bus voltage
U_c = VSC side AC voltage
δ = Lagging angle between U_c and U_s.
X = Converter reactance
M = PWM modulation index

This kind of method may be further developed for providing a safer and more reliable way of designing blackstart schemes.

7.7. Renewable Energy Used as Power System Source for Black Start

The increase of wind power production in recent years has been considered an alternative energy source to the black start scheme. However, high variability and intermittency of renewable sources in the power generation promotes the use of energy storage systems. ESS enables the connection of a black start system in order to provide a quick response speed and flexible power regulation. Under this context, the renewable energy production offshore and onshore can be an option to participate in black start [11,62]. However, the renewable energy integration cannot provide an inertia or frequency response as the traditional synchronous generators do. For this reason, new methods of control based on energy storage systems for frequency regulation during black start have been developed [13]. Finally, the higher requirements on the features of converter voltage level, system dynamics design, and system power quality have been generated with special attention to research about the technology based on high voltage direct current transmission and voltage source converters used with offshore wind [67].

8. Rising Applications and Future Challenges

As VSC-HVDC technologies will continue to have an important share of direct current transmission, there will be huge opportunities for further development on both its main mechanisms and alternate emerging applications, e.g., restoration mechanisms or secondary services for increasing the grid's resilience. There are bold analyses like that of [68], which propose the implementation of DC distribution systems, further propelling DC technologies for future power grids.

As stated in [23], the need for further inclusion of low-carbon generation will give HVDC technology an opportunity to thrive on developing Smart Grids. Some examples of huge potential with this technology include offshore renewable interconnection, unsynchronized networks links, and reinforcements to actual AC grids. Therefore, as the increasing application of VSC HVDC becomes a reality, any solution that can bring added value to this technology by enhancing the grid's performance has to be taken into account.

Other future challenges will involve the development of economic analyses for VSC-HVDC restoration schemes, as this has not been explored widely in the literature yet. Schemes for remunerating DC links for network support for each particular case would also be an important next step towards their materialization.

9. Conclusions

In this proposal, the theoretical and the advantages and disadvantages of the VSC-HVDC systems technology implemented in black start schemes were presented. This review was done by exploring and selecting recent research works to give the reader a head start before delving deeper into this subject, which will continue to be explored in upcoming years. According to the review done, VSC-HVDC technologies, either single or multi-terminal, hold a huge potential for developing supporting functions and ancillary services to electric grids during restoration processes. In order to achieve a faster recovery rate, frequency stability, and rapid controllability under dynamic changes during faults or undesired events, i.e., an increase black start capability, this review introduced promising emerging solutions for VSC-HVDC systems and presented future research directions. Finally, this paper aimed to serve as an introduction to HVDC and VSC technologies used for black start restorations. The diversity of the assistance methods explored above shows the outstanding performance and key role that this technology may bring to future power networks in the search for improved security, reliability, and resilience.

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