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Requirements for Fault Protection in HVDC Grids

D.M. Larruskain, O. Abarrategui, I. Zamora, G. Buigues, V. Valverde, A. Iturregi

Department of Electrical Engineering
EUITMOP - UPV/EHU
Rafael Moreno "Pitxitxi" 2, 48013 Bilbao (Spain)

Phone/Fax number:+0034 946014970, e-mail: marene.larruskain@ehu.es

Abstract. Conventional Voltage Source Converters (VSC) cannot interrupt DC fault currents and DC circuit breakers are not yet commercially available for HVDC power ratings. Thus, the protection of VSC-HVDC systems is still an obstacle for the development of this technology. The features of VSC-HVDC systems make them suitable for implementing HVDC grids. Nevertheless, HVDC grids are more complex than point-to-point links. Accordingly, the fault protection of these HVDC grids is a bigger challenge due to the specific requirements of DC grids. Nowadays there is no real HVDC grid operating, but it is expected that in the near future HVDC grids will be widespread, reinforcing the predominant AC systems. In this paper, the protection required by HVDC grids is thoroughly analyzed.

Key words

Circuit Breaker, HVDC Grid, Multiterminal, Voltage Sourced Converter.

1. Introduction

Most HVDC systems are point-to-point links where a certain amount of energy is exchanged. Nevertheless, there are a few HVDC multi-terminal (MT) systems which have been operating for a significant interval, i.e. Italy – Corsica – Sardinia transmission and Quebec – New England transmission. Both schemes, which are based on Line Commutated Converters (LCC) technology, have three operating converters.

However, last years, a new technology has emerged, VSC-HVDC, with new capabilities (independent and fast control of active and reactive power, black-start capability, etc.) which make this option more suitable for new applications. One of the most relevant applications is the multi-terminal schemes, due to the fact that the power flow is reversed changing the current and not the voltage as in the case of classical LCCs. Thus, the reversal is easier than in LCC technology. However, the reliable protection of VSC-HVDC systems is still a challenge [1], mainly, due to the fact that DC fault currents must be detected and extinguished in a short time. In fact, the overcurrent withstand capability of VSCs is extremely limited.

Modular Multilevel Converters (MMC) are a promising VSC-HVDC technology, with more suitable fault behaviour. Anyway, MMCs are not able to control fault currents. Nowadays there are a few fault-blocking converters that can control fault currents (full-bridge MMC and variants) but with significant drawbacks, i.e. cost, losses, additional switching states, etc.

DC grids are suitable, among other uses, for offshore systems due to the problems related to long AC cables and to connect remote renewable power resources [2]. This way, there are projects for DC grids which will interconnect wind power in the North and Baltic Sea and solar power in North Africa and Medium East [3][4]. In 2013, the first multi-terminal VSC-HVDC system, based on MMC technology, has been commissioned in China, with design ratings of ±160 kV - 200/100/50 MW, and a succession of underground, undersea and overhead lines. The system has the objective of integrating the wind power generated in Naoao island into the inland power system. This link, being the first operating VSC-HVDC MT system, represents an important milestone in the development of future HVDC grids

Next years it is expected that the relevance of multi-terminal schemes will grow considerably, as DC grids are created. The construction of these DC grids will take a long time since there are still some technical limitations that must be overcome and they require a large investment. In this paper, HVDC grids are analyzed focusing mainly on the grid features and the fault protection. Finally, DC CBs are overviewed.

2. HVDC Grid Features

Multi-terminal systems consist of three or more converters which are interconnected creating a HVDC network. Nevertheless, it is not so obvious what conditions have to be met by DC grids. The European Association "Friends of the Supergrid" defines the Supergrid as "an electricity transmission system, mainly based on direct current, designed to facilitate large-scale sustainable power generation in remote areas for transmission to centers of consumption, one of whose fundamental attributes will be the enhancement of the market in electricity".

This way, the DC grid will be able to integrate large renewable resources. It will also include medium scale storage and backup devices connected to the AC grid and distributed energy resources connected to the distribution network [5]. Definitely, the Supergrid will constitute an intelligent system to manage the energy demand, variable sources and storage. For that purpose, it will be necessary a real time communication system.

Regarding the transmission technologies that can be used to implement a DC grid, LCC and VSC technologies have different features and limitations. Among them, MMC VSC is apparently the best option for DC grids given that this technology presents low switching losses in permanent operation as well as a better fault performance.

HVDC technology has several interesting characteristics, this way, DC Converters increase the controllability and improve the dynamics of both, AC and DC grids [6]. It must not be forgotten that there is an interaction between the DC grid and the extensive AC grid. Therefore, multi-terminal systems increase power system stability during faults and reliability of both grids. Moreover, AC grid can be separated into zones with the objective of avoiding the spreading of faults and cascading blackouts.

A. DC Network topologies

There are different MT topologies to develop a DC grid. The most common ones are radial and meshed grid designs. Radial structure is similar to the traditional AC distribution system, without loops. It benefits from the easy control and relay protection system. Nevertheless, the reliability is lower due to the single-ended power supply. On the other hand, meshed structure presents a higher reliability due to the redundant supply channels, but the costs are also higher.

These topologies must be compared and evaluated in terms of overall system losses, transient fault currents, and post-fault contingencies in order to determine which one has higher benefits. No DC topology can optimally satisfy all aspects at the same time, so case by case analysis must be done, for every network and power flow scenario [7]. For a reference generation scenario in 2030, meshed designs showed to have a small economic advantage over a radial approach [5].

B. Development of DC Grids

Nowadays, most of the HVDC systems installed all around the world have been implemented freely by each manufacturer. It is logic that the construction of DC grids starts connecting some of the existing DC links to each other, as the setting up of the preliminary steps. Thus, the different systems will have to be adapted between them. In that sense, for the efficient development of a DC grid, it would be really helpful to have some standards. This way, if the following concepts are clarified, the planning criteria for different manufacturers could be resembled and the development of the DC grid would be eased [5]:

1) *DC voltage levels.*
2) *DC grid topologies.*
3) *Fault behavior:* short circuit currents of converter stations and location of fault clearing devices, at each converter station or at each DC feeder.
4) *Power system protection:* differentiation between normal transients and faults, relays and communication to selectively detect faults and fault clearing mechanisms, including fault current and overvoltage limitation.
5) *Converter control and protection:* sequences for start-up and shut-down, converter station control.
6) *HVDC grid controls*

Observing the aforementioned facts, it is obvious that the protection and control strategies for the different converters of the grid are still a huge obstacle for building future HVDC grids. Next section the requirements for the protection of HVDC systems is analyzed.

3. Protection of HVDC Grids

Grids are more demanding than point-to-point links, both in AC and DC systems. Anyway, the protection of DC systems is a more demanding task, mainly because of the absence of natural current zero crossing. Besides, VSC-HVDC converters are highly sensitive to overcurrents. The main features of a DC or AC grid protection system are following detailed [2]:

1) *Sensitivity:* accurate detection of any fault without exception.
2) *Selectivity:* discrimination between normal operation and fault condition. Therefore, protections should only operate in case of fault, and just if the fault is located in its own coverage domain.
3) *Speed:* the faults must be interrupted before they can damage equipment or can no longer be interrupted by the circuit breakers.
4) *Reliability:* reliable operation and a backup system in case of failure of the primary protection system.
5) *Robustness:* fault detection in normal mode and in degraded mode. Discrimination of faults from any other operation occurring (setpoint changes, operations, etc.)
6) *Seamless:* after clearing the fault, the remaining part of the system should continue operating securely.

These features influence the design of the converters and the DC grid, e.g. they determine the detection and action sequence. In addition, they also determine how the DC grid will look like. Finally, for a complete protection, DC breakers are needed at both ends of each cable or overhead line.

Conventional AC side CBs usually protect VSC-HVDC links, nevertheless these devices are not suitable for protecting HVDC grids. AC CBs require the de-energization of the entire system which would result in an unacceptably large loss of infeed, and this is not feasible for a DC grid. For a reliable protection, HVDC grids require a fast and selective isolation of the faulted line, in order that the remaining lines can continue operating normally [8].

Thus, HVDC grids require reliable and robust protection devices. DC CBs must be improved before being ready for protecting HVDC grids. Among other features, the breaking time must be reduced. In section 4 a more thorough revision of DC CBs is carried out.

Following the most relevant features for the protection of DC grids are analyzed.

A. Control

The control method should govern the basic functions of each converter and coordinate all the converters of the grid with a proper control strategy in consonance with the different operating modes. It must also take care of the various disturbances that can affect the system. Additionally, the power flow through a HVDC line needs to be controlled to avoid exceeding the power rating of its components.

There are different control strategies available. In order to choose the most effective strategy, the grid topology is a major consideration.

For instance, in the case of parallel MTDC systems, the basis of the control goal is to maintain a constant DC voltage and power balance [9]. Whereas in radial HVDC grid systems, the power flow through each line can be controlled by the DC voltages of the individual converter stations [5].

In the case of meshed systems, they have more than one line connecting two converter stations, at least partly. In these systems, the flow through parallel paths depends on the DC voltage at the converter stations and on the line impedances. Thus, such systems may need additional DC Line Power Flow Controllers to achieve a required power flow. DC Line Power Flow Controllers will insert a certain DC voltage in series with the line, in order to control the current. DC Line Power Flow Controllers are still under development.

However, in all cases the power exchange between the AC system and the DC grid can be exactly controlled by the converter stations. This provides an additional degree of freedom for the operators of the combined AC and DC grid which can be used to influence the load flow conditions in the surrounding AC systems.

B. Detection

Fault detection and location is important, especially on multi terminal systems, in order to isolate the fault in a short time and restore the system as soon as possible [1].

The main issues of fault location are: fault resistance and grounding. The fault resistance can change from zero to dozens of ohms, which has influence over the location of the fault. Besides, regarding the type of neutral grounding, MTDC systems can be divided into two categories: grounding (including high-resistance grounding) and non-grounding systems [10][11]. The non-grounding systems can be used for a better reliability of power supply in pole-to-ground faults. Just like in AC systems, those issues have different fault responses.

Fault location plays two important roles in power system. On the one hand, the identification of fault section should be quick to initiate the relay protection system in a short time and thus, avoid the loss caused by overcurrent. On the other hand, the identification of the specific fault point should be remarkably accurate [12].

Finally, fault detection and location with sensitivity and selectivity in HVDC grids is an important hurdle mainly because the reaction time available is extremely small, typically 1-2 ms, before the fault current level is so high that it is difficult to interrupt. A solid methodology must be developed.

C. Coordination

Converters in a HVDC grid must be well coordinated in order to maintain the power balance, satisfactory power transmission and a solid DC voltage [13].

When a short circuit appears in a HVDC grid, the fault will propagate through the DC circuit and appear at every converter station as a sudden DC voltage drop. Therefore, the protection systems of the converter stations will respond accordingly interrupting the fault current and isolating the faulty section. Thus, a fast communication system between the converter stations is required to provide selective fault isolation. Afterwards, the remaining system can recover fast. Selective protection systems for HVDC grids are currently under development [5].

However, the sustaining of DC voltage and the DC Load Flow control can be done without communication between the converter stations. In any case, communication is needed to provide the required coordination between every converter station (e.g. transmission of signals: start-up or shut-down, set-points, etc.).

4. DC Circuit Breakers

Nowadays, there are some technical limitations for creating a DC grid [14]. Several components must be developed and available at competitive prices. Among them, DC circuit breakers are probably the most relevant ones. Therefore, before DC CBs are feasible for being employed in DC grids, several concepts must be improved [15], mainly in terms of on-state losses and breaking time.

As the DC current does not naturally have zero crossing, the DC CBs must bring the current to zero in order to suppress the arc and to interrupt the current. The CB must also dissipate the energy stored in the system inductance and withstand the voltage response of the network after current interruption. Following the most relevant operation principles for DC CBs are reviewed.

A. Resonant DC CB

Resonant DC CBs are based on a resonant circuit composed of a capacitance and an inductance. There can be passive or active resonant circuits for forcing the zero crossing of the DC current. These CBs have an interruption time of 30-100 ms, which is rather high for DC grids. Accordingly, nowadays the research of DC CBs is focused mainly in other types of CBs [16].

B. Solid-State DC CB

Solid state DC CBs are based on quick semiconductor devices, such as IGBTs. The semiconductors are placed usually on the main current flow line, this way the operation times are very short but the on-state losses are rather high. In order to reduce those losses, some proposals use a fast mechanical switch in the main circuit, creating a hybrid CB (Fig. 1).

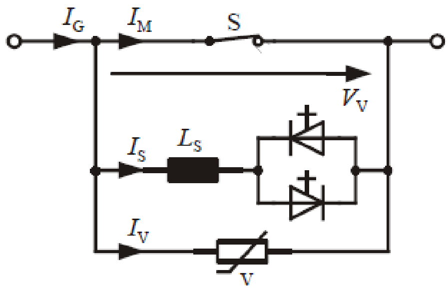

Fig. 1. Conventional Hybrid Circuit Breaker [17].

A typical hybrid solid-state DC CB consists of a fast mechanical switch in the main line, a parallel path composed of semiconductor devices which redirect the fault current from the main path, allowing the opening of the mechanical switch. In such manner that finally the fault current can be switched off [17]. Currently ABB is developing a hybrid solid-state DC CB which combines IGBTs with a mechanical ultra-fast switch [18].

C. DC/DC Converter

There are many feasible technologies for DC/DC converters, such as LCL thyristor (Fig. 2)[19] and DC/DC chopper (Fig. 3)[20], which have different applications. Aside from the evident function of interconnecting DC grids of different voltage levels, DC/DC converters have several distinct applications.

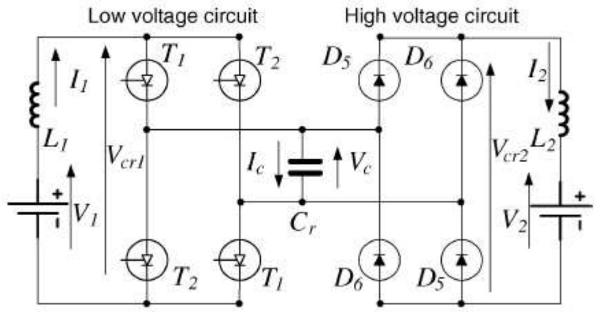

Fig. 2. DC/DC Converter, unidirectional step up converter [19].

In the case of DC grids, these devices can perform voltage stepping, DC power or DC voltage regulation, interface different technologies (i.e., LCC and VSC, monopolar and bipolar, etc.) and DC fault isolation [19]. This way, some DC/DC converters have capability to interrupt DC faults without any control action or causing any overvoltage. But these devices have rather high losses during normal operation. In any case, this is a rather new research area and must be still developed.

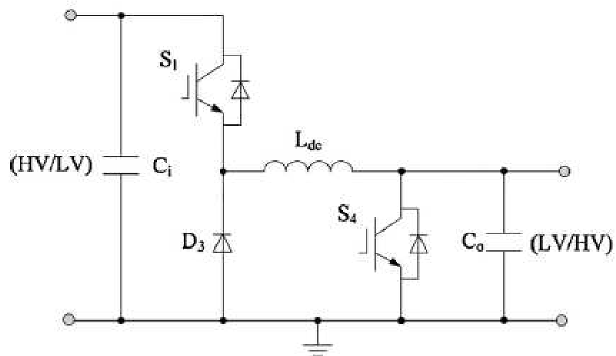

Fig. 3. DC chopper, two-switch topology [20].

5. Conclusion

The fault characteristics of a MT MMC-HVDC system are different from a point-to-point two-level VSC-HVDC. The control and protection of multi-terminal MMC-HVDC system are more complex, because the MT system must assure that when a fault appears in a zone the non faulted converters and lines maintain secure operation with the coordinated strategy between stations. This way, coordinated control method among converters is particularly relevant in MTDC systems. In fact, grid protection is one of the main difficulties of HVDC grids.

In general, fast fault clearing and active power recovery in case for DC faults is important to maintain power system integrity and stability. Actually, there is hardly any experience with fault handling in HVDC multi-terminal systems. In the near future, agreements of the transmission system operators involved will define the requirements with respect to the fault behavior or ENTSO-E Network Code.

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