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DC Switchyard Configurations for the Integration of Distributed Energy Resources

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Abstract.
HVDC supergrid must grow in an organized way. The objective of HVDC substations will be to integrate generation groups and occasionally connect them to the AC network. That way, all substations will not be identical and their relevance will not be the same.
In AC substations, network topological changes are made to limit the short circuit current contributions, perform load distributions and allow maintenance work when the application of restrictions is necessary, without compromising generation. These maintenance tasks should allow the exploitation of the network without making concessions on the stability of the system.
DC networks do not require topological changes in the network to distribute loads, its utility would be reduced to facilitate maintenance tasks and minimize the possible effects of faults. However, it must be discussed which is the most suitable switchyard or whether more than one switchyard are required such as in AC networks.
In the paper the usual topologies and switchyard configurations are analyzed and compared to determine if the architectures inherited from the AC grids can be used in the future HVDC supergrid. Several DC switchyard configurations are also discussed. Finally, the most suitable configurations are compared and applied to a study case.

Key words

Distributed Energy Resource, Offshore, Tpology, Switchyard, HVDC Grid.

1. Introduction

An energy planning based on Distributed Energy Resources (DER) does not guarantee power availability given the variable and non-manageable character of this energy. Therefore DER must be complemented with flexible and firm generation that will be able to respond to demand with security of supply. Independently, it is taken for granted that the current development of offshore generations should be oriented to an HVDC supergrid with both offshore and onshore transboundary links that could minimize the intrinsic variability of this generation, at the origin [1].

Onshore links must make the most of the existing network, which is only possible with expensive equipment (topologic configuration, etc.). Besides, nowadays for distribution voltage levels it is inconceivable the concept of those equipments due to their high cost (e.g. phase shifter). Nevertheless, if the objective is to integrate the distributed generation, the access conditions of this equipment should be loosen.

The interconnection of offshore wind farms, creating a network will not only reduce the intermittent nature of the wind. Moreover, that grid will provide redundancy in case of a transmission system failure and will give possibility to reduce the number of HVDC converters, minimizing the investment costs and the conversion losses [2]. There are many obstacles that must be overcome to create an international grid: technical challenges, as well as the development of economical and legal framework.

The HVDC network should complement the extensive AC network. That way, substations would have a similar operability, but both networks should be complementary.

In the paper the HVDC switchgear is analyzed. HVDC topologies for integrating the power generated by DER, and more precisely by considerable plants distributed in large areas are discussed and compared in several terms, such as flexibility and exploitation. Finally, the most suitable DC switchyard will be discussed.

2. DC switchgear

The selective protection of HVDC supergrid requires the use of HVDC circuit breakers (CB). Besides, the interruption of HVDC short circuits is a demanding task since DC does not have a zero crossing and the energy stored in the system inductances must be dissipated.

There are mainly three HVDC CB technologies: mechanical, solid state (SS) and hybrid CB, Table I shows the characteristics of each type.

Table I Types of CB.

	MECHAN.	**SOLID STATE (SS)**	**HYBRID**
Advantages	Cheap Developed over the past 5 decades.	Fast speed (current interruption). Capital cost.	Fast speed. Low steady-state losses
Disadvantages	Low speed (current interruption).	Breaks current in one direction. Larger losses than mechanical.	Development required.

Nowadays the most developed one is the hybrid technology [3], as shown in Fig. 1, nevertheless there are still big limitations.

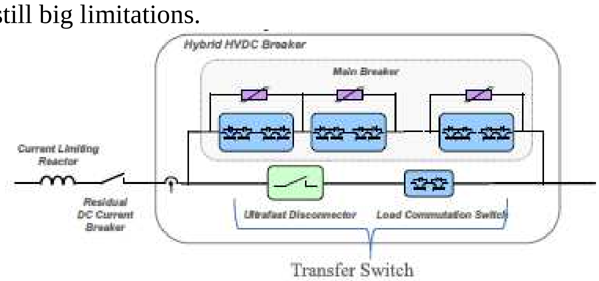

Fig.1. Hybrid HVDC CB [8].

3. HVDC topologies

HVDC network design as well as equipment, must fulfil the same current requirements of HVAC network. Therefore, the Grid Codes (GC) of the Transmission System Operators (TSO) and Distribution System Operators (DSO) must be complied with. The starting point is an energy scenario of high DER penetration. Thus, the first step should be to form groups of generation aggregators. In this paper each group of generators will be represented by a single device.

TSOs have conditioning factors for maintaining system stability in contingency situations due to loss of generation [4-5]. Thus, when planning HVDC grids, it is necessary to renounce those configurations in which the loss of a single device will cause a bigger generation loss than that indicated in these GC. It is imperative to promote a HVDC meshed grid with a design capable of covering these contingencies.

In the paper, the most common topologies for HVAC grids will be considered based on the favourable and extent background of AC grids.

A. Point-to Point Topology

Point-to-point topology is composed of one sending and one receiving converter station, as shown in Fig. 1. Therefore, point-to-point connections should be limited to installed generation groups, to fulfil the security requirements *n-1*. Bipolar connection can provide a redundancy in case of disturbances.

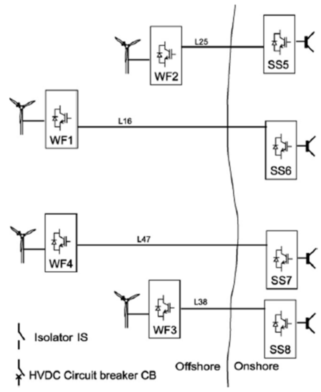

Fig. 2. Point-to-point topology [6].

B. Ring Topology

Ring topology, Fig. 2, is a meshed grid, defined in [7] as "*a system consisting of at least three converter stations and which includes at least one mesh formed by transmission lines (overhead lines and/or cables)*".

The ring topology allows that each generator has its own limit, as long as there are several points of interconnection with the AC network.

During possible maintenance work of one of the interconnections of the ring, the stability values given would not be covered. Therefore, the maintenance ranges of the equipment and the number of elements of the ring, become relevant in the assessment of the risk assumed.

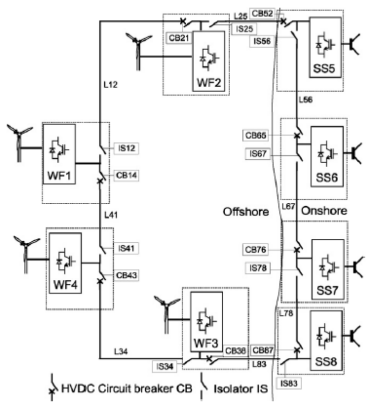

Fig. 3. Ring connection [6].

C. *Meshed Multi-Terminal Topology*

In order to integrate properly the generation, the DC network model that would comply with the requirements should be a model similar to the actual one. Thus, the generation groups should not suppose a problem of stability or risk for the system when a situation of *n-1* occurred, either for maintenance or unexpected failure of one of the equipment. It can be concluded that this is the desirable DC network architecture (shown in Fig. 3).

This topology consists of simple extensions of groups connected to the meshed AC grid onshore. Nevertheless, the connection and disconnection of large groupings increase the unavailability times. It is, therefore, a topology in which significant modifications are not expected, just power increases of the groups. This could be the germ of an offshore network structure, with as many connections to the onshore network as are necessary to maintain the stability criteria discussed, as well as those based on *n-1*.

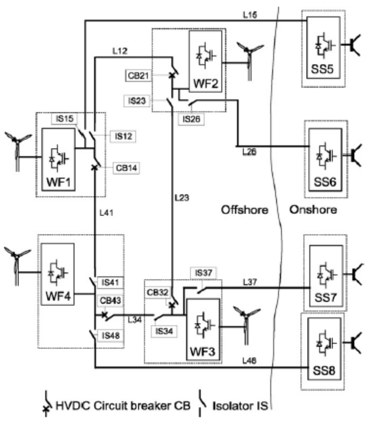

Fig. 4. Meshed Multi-Terminal Topology [6].

4. DC switchyard

Once the dimensions of the grid are established, the discussion should go backwards to the detail of each group and define the model of the link node. Based on AC substation architectures, there is a number of configurations with different functionality.

The proposed configurations have been analyzed taking into account criteria of Reliability, Availability and Maintenance (RAM) [9], fulfilling the *n-1* criterion for a given power. It is undoubtedly a very restrictive criterion, when other factors such as the probability of occurrence are currently being taken into account.

Therefore RAM is employed to characterize system performance in the following terms:

- Readiness of the system for use.
- System performance of the intended function.
- Endure the system in an operational state over its specified useful life.

In response to these indications, the following configurations can be considered in the design phase:

A. Single busbar

The most simple busbar switchyard is a single busbar. The connections between the various parks will have the same structure as current point-to-point radial connections. It is the proposed solution for the network configuration shown in Fig. 2.

B. Double busbar

To achieve the necessary redundancy in meshed networks, configurations based on double busbars are required.

1) *One Breaker*. This configuration does not provide advantages over maintenance or reliability. For this reason the main utility will be an intermediate step on the following double busbar configurations.

2) *Two Breakers*. It is one of the most widespread solutions because of the advantages it provides. The double breaker double busbar switchyard (DBDB), with hybrid CBs, maintains the same reliability, in case of failure, during periods of maintenance of the main breaker.

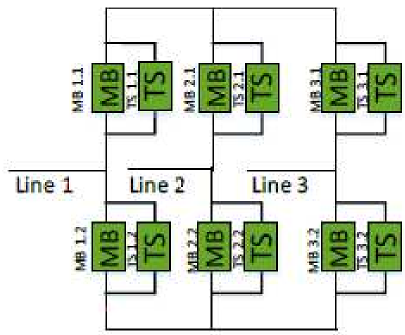

Fig. 6. Double Breaker Double Busbar Switchyard [8].

DBDB does not present limits regarding the number of lines to be connected. Therefore, it can be considered as an appropriate configuration for possible extensions.

Regarding the availability of HVDC CB, there is a proposal that reduces the number of Main Switches (MB), compared to the double busbar configuration, increasing the number of equipment such as the Transfer Switch (TS) and the CB, getting a more compact and similar functionality.

This configuration, named Multiple Transfer Switches Multiple Main Breakers Switchyard (MTSMB), based on [8], aims to solve the problem of faults, with a more compact configuration and fewer elements. Among other disadvantages this switchyard is limited to configurations of three lines. Fig. 5 depicts the operation of a MTSMB switchyard that connects three lines with two MB when there is a fault at Network A. The fault current (green line) is redirected in two paths as shown in Fig. 5(a) with proper switching of the transfer switches, (red switches indicate "open" while those green ones indicate "close"). The MBs are opened in (b) to interrupt the fault currents. In (c) the MBs and TSs are reclosed once the faulted line is isolated

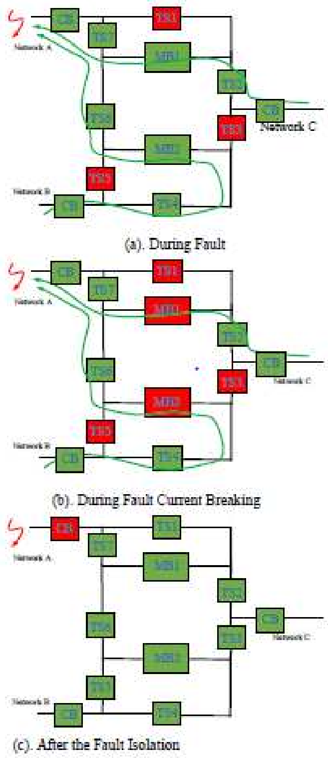

Fig. 5. MTSMB switchyard. Three lines connected with two MBs [8].

3) *Breaker and a half.* The current state of the art on DC switches and their predictable high cost, makes necessary an analysis of the usual configurations to try to optimize them. These are shown with the main element, as a single device, in which all the additional equipment necessary both for normal operation and failure case are included.

In [10], these provisions guarantee a similar degree of reliability, during faults and maintenance, reducing the number of switching devices. The combination of unidirectional switches (conduct towards busbar) and a bidireccional switch (half breaker) protect against faults in lines, busbar, etc.

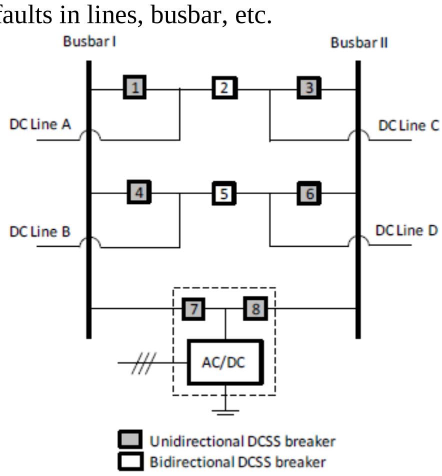

Fig. 7. DC busbar switchyard with unidirectional and bidirectional DC solid state CBs.

In [11], a simplification is based on the fact that the steady state DC fault current is supplied from the AC grid through VSC terminals while DC lines only supply transient DC current from the discharge of the line cable capacitances. Faults at local HVDC station are cleared by fast DC SS CBs (the quick elimination of the current contribution from the local HVDC station removes the main fault contribution), in Fig. 8(a) CBs 4 and 5 or 7 in Fig. 8(b). Faults in the lines are cleared by mechanical DC breakers that interconnect the switchyards.

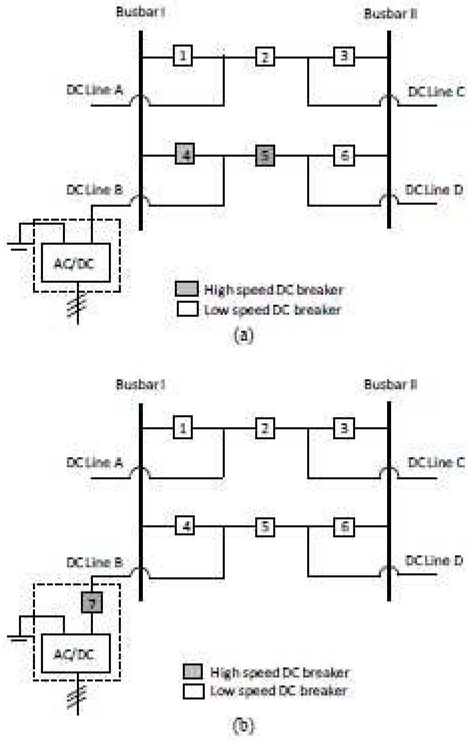

Fig. 8. DC busbar switchyard with fast SS CB and slow mechanical CB.

4) *Configuration in H.* The configuration in H is a solution that improves maintenance and reliability in the case of faults in the connection line.

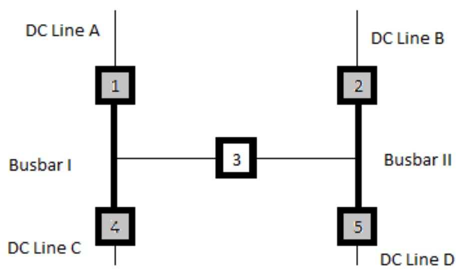

Fig. 9. DC *H* busbar switchyard with unidirectional and bidirectional DC SS CB.

The usual operation is carried out with “switch 3” open. Accordingly, generation groupings behave like two independent point-to-point systems. However, in the event of maintenance or failure of one of the lines, the service is maintained by closing “switch 3”.

Consequently, with “switch 3” it is possible to maintain 100% of the service when there is *n-1* of any of the lines.

This configuration is valid for two connection lines, and implies equipment oversizing.

5) Summary.

The main advantages and disadvantages of the configurations analyzed in this section are summarized taking into account RAM criteria, as described in Table II.

Table II. – Typical RAM performance requirements [13]

	MONOPOLE ARRANGMENT	BIPOLE ARRANGMENT
Forced outage rate.	3 to 4 per year	100% power, 6 to 8 per year 50% power, 0.05 per year
Forced energy unavailiability.	up to 0,5%	100% power, up to 1% 50% power, up to 0.02%
Schedule energy unavailiability.	up to 1%	100% power, less than 2% 50% power, less than 0.1%
Energy availiability.	up to 98.5%	100% power, up to 97% 50% power, up to 99.9%

Note:
100% power, both poles are available for power transfer.
50% power, at least one pole is available for power transfer.

Next, the proposed most suitable configurations for HVDC networks are compared in Table III.

Table III – DC switchyard for HVDC networks

	MTSMB	DBDB	Breaker and a Half
RAM	Low (loss of functionality due to maintenance or failure of one of the MB)	Meets table II requirements (bipole)	Meets table II requirements (bipole)
Footprint	Compact	Open architecture (less compact)	Compact
Maximum connecting lines	3 lines	No limits	No limits
Other characteristics	Increase in the number of secondary equipment. Fewer elements		Prototypes Further development required

5. Study Case

As a summary of the discussed configurations, the most appropriate switchyard configurations are selected for the network model proposed by CIGRE [12], Fig. 10, in table IV.

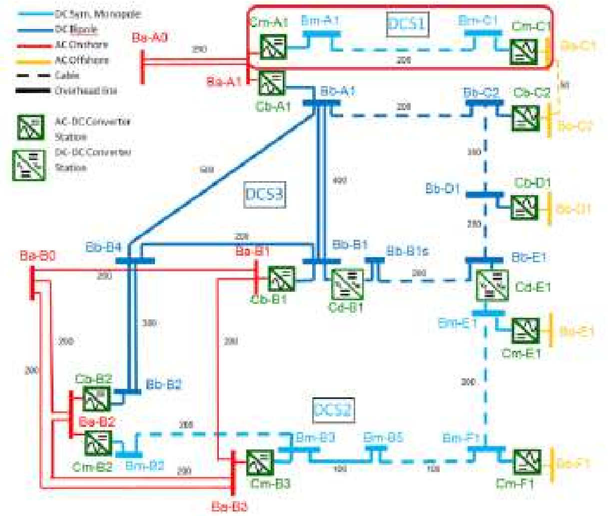

Fig. 10. CIGRE B4 DC Grid Test System [12].

Table IV. – DC Switchyard correspondence

	FIGURE	TYPE
Bm-C1 Bm-B2 Bb-B1	2	Single busbar
Bb-C2 Bd-D1 Bd-E1 Bm-E1 Bm-F1 Bm-B5	5, 6	Double busbar (MTSMB, DBDB)
Bm-A1 Bb-A1 Bb-B1 Bb-B4 Bb-B2 Bm-B2 Bm-B3	7,8	Double busbar (Breaker and a half)

The configurations with a high RAM are located in those connections with AC grids and buses that group several lines.

5. Conclusion

HVDC supergrid is necessary to integrate large-scale offshore wind power. The development of this supergrid, creates the need to use busbar to connect these infeeds.
The usual configurations for AC switchyard are valid as a model for the development of future DC switchyard. With these, reliability, compliance with *n-1*, and maintainability of the equipment that will form this supergrid are maintained.

As in the case of AC network, in this supergrid the importance of the substation, in terms of connections, loss of transmitted energy or connection with the AC network, determines the size of this, as well as the reliability requirements that must be provided to the grid.

There are also configurations that achieve greater compactness without reducing their functionality, as well as others that explore solutions based on hybrid CBs.

In spite of the pending technical challenges, in terms of UHVDC cable development, DC breakers, there are solutions to plan and develop, with guarantees of security of supply, a HVDC grid that is developed gradually, connecting together the existing point to point HVDC schemes.

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