FLEXIBLE CONVERTERS FOR MESHED HVDC GRIDS: FROM FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS) TO FLEXIBLE DC GRIDS

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Abstract

Flexible Alternating Current Transmission Systems(FACTS)haveachievedtoenhancetheflexibilityofmodernAC power systems, by providing fast, reliable and controllablesolutions to steer the power flows and voltages in the network.The proliferation of High Voltage Direct Current (HVDC) trans-mission systems is leading to the opportunity of interconnectingseveral HVDC systems forming HVDC Supergrids. Such gridscan eventually evolve to meshed systems which interconnect anumber of different AC power systems and large scale offshorewind (or other renewable sources) power plants and clusters.While such heavily meshed systems can be considered futuristicandwillnotcertainlyhappeninthenearfuture,thesectoriswitnessinginitialstepsinthis direction.Inordertoensurethe flexibility and controllability of meshed DC grids, the shuntconnected AC-DC converters can be combined with additionalsimple and flexible DC-DC converters which can directly controlcurrentandpowerthroughthelines.The proposedDC-DCconverters can provide a range of services to the HVDC grid,including power flow control capability, ancillary services for theHVDC grid or adjacent grids, stability improvement, oscillationdamping, pole balancing and voltage control. The present paperpresents relevant developments from industry and academia inthe direction of the development of these converters, consideringtechnical concepts, converter functionalities and possible integra-tion with other existing systems. The paper explores a possiblevision on the development of future meshed HVDC grids anddiscussestheroleoftheproposedconvertersinsuchgrids.

***IndexTerms*— Currentflowconverters,HVDCsystems,HVDCgrids,flexiblepowersystems,FACTS.**

I. INTRODUCTION

MOST countries worldwide have set a series of ambitious climate and energy targets to combat climate changewhile increasing energy security. While the strategy is very dependant on the policies in each specific country, the role of offshore generation (especially wind) will be decisive in order to meet current and future energy challenges. Offshore wind power plants present a number of benefits compared to traditional onshore installations [1]: the availability of higher wind speed, the possibility of transporting very large structures (allowing larger wind turbines) and the limited available inlandlocations to install new wind farms in some countries (mainlyinEurope).

Offshore generation facilities can be connected to the main50Hzor60HzACgridusingtransmissionsystemsbasedonACorDCtechnology[1].Thechoicebetweenthesetechnologiesdependsonthecostoftheinstallationwhichdepends in turn on the transmission distance and power rating.Theneedtocompensatefortheimpedanceofthecablesin ACtransmission makes its

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price grow with the distance at a higherratethanDCtransmissionwhereasDCtransmissionimpliesa high fixed cost due to the need of large power converters.Thus,thereisabreak-evendistancefromwhichtheDCoptionbecomes lower priced than AC [2]. For submarine cables thebreak-evendistanceisusuallyaround100km.

Until the last decade, high voltage direct current (HVDC)transmission systems were mostly based on current fed Line-CommutatedConverters(LCC).Newconvertertopologiesand lower priced fast-switching semiconductors made possi-ble to build Voltage-Sourced Converter (VSC) based HVDCtransmissionsystems.ThebenefitsofusingVSCandfastswitching are the ability to independently control the activeandreactivepowerwhilereducingthesizeoftheoutputfiltersneededtohavealowharmonicdistortion[1],[2].Thislastbenefitisespeciallyrelevantforoffshoreapplicationswhere the footprint and weight of the converter stations is acritical issue. Novel VSC-HVDC designs based on modularmultilevel converters (MMC) are arriving to efficiencies closetoLCCconverters.OnedrawbackofVSC-HVDCisthatthe achieved voltage and current levels (although it has beenincreasing substantially in the last decade) is still lower thanLCC. In any case, mainly due to the footprint and weightissues, all the offshore power plants which need a DC cableconnection are being planned with VSC-HVDC transmissiontechnology. The worlds first VSC-HVDC for offshore powertransmission (BorWin1) was successfully commissioned offthecoastofGermanyin2009.AnumberofVSC-HVDCconverterstationsforoffshorewindpowerplants(DolWin1, 2 & 3, BorWin 2, HelWin 1&2, SylWin 1&2) are beinginstalled and commissioned in the North Sea since then. WhileVSC-HVDC technologies based on MMC have motivated agreat break-through in power transmission technology, remoteoffshore wind power plants have a crucial challenge whichneeds to be addressed: the cost of the overall offshore windpowerplant,alsoincludingtheplatforms,isveryexpensive.

Industryandacademiahaverespondedtothischallenge by proposing some alternative designs which aim at reducingcost in different subsystems: diode rectifiers or LCC-HVDCconverterscanbeusedintheoffshoreconverterstation[3],[4];Hybrid VSC/LCC transmission technology can be used withdifferentconvertersonshoreandoffshore[5],[6];Seriesorhy-bridseries-parallelDCcollectiongridsforoffshorewindfarmscan be used [7], [8]; Converter reduction or elimination in thewindturbines,byusingtheVSC-HVDCconvertertomodulatetheoffshorefrequencyandtheaveragewindturbinespeed[9], [10]. While the proposed solutions bring some promisingideas for cost reduction of offshore wind power plants, theintegrationofthesesystemswiththeHVDCtransmissioncan bring some new technical challenges for the transmissionlinks. A clear example is the possible deployment of converterstations based on diode rectifiers. Such a technology can bringa cost reduction, but the lack of controllability of the diodeswill pose some operation, protection and stability challengeswhichneedtobeaddressed.

It is important to remark that converter stations based on technologies not able of forming a grid (such as diode rectifier units and LCC converter stations) require external devices to form the offshore AC grid and control the frequency. This can be provided by an appropriate coordinated control of a plurality of wind turbines running in grid forming mode, or by additional equipment such as STATCOM systems or batteries interfaced with Voltage Source Converters (VSC). These options have been studied in references [11]–[13] and are being explored in the frame of the EU project Promotion and have been proposed by relevant manufacturers [15]. Currently, existing VSC-HVDC transmission systems in Europe use point-to-point connections. This means that each individual converter is directly connected to another single converter by means of a DC cable. More terminals can be added (keeping a radial structure) evolving into the so-called multiterminal HVDC (M-HVDC) scheme. Two multiterminal (Nan'ao, 3 terminals, and

Zhoushan, 5 terminals) HVDC projects are already in operation in China [16], while some projects are under study in the rest of the world. Furthermore, there exist the opportunity to create meshed HVDC grids off- shore, both interconnecting different countries and transmitting all the offshore power generated.

Figure 1. The European Supergrid. Source: Friends of the Supergrid

Theoffshoregridalternativecaneventuallyevolvei ntheso called Supergrid [17] (Figure 1 shows the vision of theEuropeanSupergrid).Suchaconceptshowsanu mberofadvantages (comparing to other transmission options such aspointtopointHVDCorHVAC)andisdefinitelyo ptimumbut requires standardization and coordination. On the otherhand, some initiatives (the most relevant in Germany [18]) aretargetingatreinforcingACpowersystemsbyintr oducinglargeVSC-HVDClinksinterconnectingtheoffshoregeneratio nplantswiththeloadcentres.

ThedevelopmentofHVDCgridspresentsan umberoftechnical challenges (There are also a number of non-technicalchallengeswhichareextremelyimpor tant,includingeco-nomical, ownership and legal aspects): optimum topologiesdefinition considering cost optimization and system reliability;Development of reliable, efficient and cost effective powerconverters (DC-DC and DC-AC) able to create independentgrids and provide support to the main AC systems; Devel-opment of technologies to ease the controllability of powerflows; HVDC circuit breaker technology with reasonable costandefficiency;Fastandreliablesystemsfor faultdetectionand isolation; Power flows control and optimization; Voltagecontrol in normal and fault conditions. The previously men-tioned challenges are certainly important and need to be (andare being) addressed in the short-medium term in order toallowthedevelopmentofHVDCgrids.

Thepresentpaperisorganizedonthebasisthat futureHVDC grids will be very complex systems, incorporating anumber of different power converters of different nature. Suchhybrid grids will be composed of VSC converters (2-level,MMChalfbridgeandMMCfullbridge),t hyristors-basedLCC converters, diode rectifier based converters and DC-DCconvertersofdifferentnature[19],[20].The hybridizationwillallowtheinterconnectionofd ifferentsub-systemsbutwillalsoimply severe limitations on the operational capacity of theinvolved converters. Specific power converters and apparatuswill be required to control the power flows, protect the powersystemandensurestability.

Thepresentpapercombinesarevisionofthest ateoftheart in the topic, with a vision on future meshed HVDC gridsincluding the proposed converters. It presents some differentdevelopmentsfromindustryandacad emiaonflexibleDC-DCconverterstobeabletodevelopflexibleHV DCgrids.The paper addresses different technical concepts, converterfunctionalitiesandpossibleintegrati onwithotherexistingsystems. The paper envisions future HVDC grids where theproposed converters can be integrated with other equipmentcost. The rest of the paper is structured asfollows. Section II synthesizes the state of the art and sum-marizes the main technologies proposed. Section III presentsthe vision of future HVDC meshed grids with the proposedflexible DC-DC converters. which prove these features. Section V discussestrends, challenges and research needs. The conclusions aresummarizedinSectionVI.

I. STATEOFTHEART

CurrentFlowControllers(CFCs)orPowerFlowControllers(PFCs)arepowerconvertersoffullorreducedsizethatcan beusedtosupporttheoveralltotheHVDC grid:parallel-connected,series-connectedandparallel-series-connecteddevices.Theseconceptsareillustratedin Fig.2.

A. *Parallel-connectedCFCs*

Parallel-connected devices are connected between the pos-itive pole and the negative pole of the transmission system[21], [22]. They are essentially DC-DC transformers with avoltagetransformerratiobetweentheinputandtheoutputthat are used to interconnect HVDC systems with differentvoltage level and can provide other functionalities as powerflow control [23]. The main drawback of parallel-connecteddevicesisthattheyhavetowithstandthe nominalvoltageof the transmission system and need to be rated for the fullpowerflowingthroughthedevice,whichcan meanhundreds ofmegawatts.Therefore,thisleadstohighcostsnotalwaysjustifiableforonlypowerflowapplications[24].

B. *Series-connectedCFCs*

Series-connectedCFCscanbesmallerdevicesandare floatingatthepositiveornegativepoleoftheHVDCsysteminsertingavariablevoltageinseries withtheline[21].Therefore,theymustnotberatedforthenominalvoltageofthetransmissionsystembutforthenominalcurrentoftheline.WithfewkVitispossibletoregulatetensorhundredsofamperessincethecable-connectedCFCsandcanmakethemmoreconvenienttoregulatecurrentflows.Anotherconsiderationregardingseriesdevicesisthattheyhavetobeplacedinthepositivepoleandalsointhenegativepole,otherwisethesymmetryofthecurrentflowislostintheHVDCgrid[23].Theycanbeclassifiedas:seriesvariableresistors,AC-DCconvertersandDCMCDCconverters.CFCsbasedonseriesvariableresistorsachievethevariablevoltagebymeansofavariableresistanceinserieswiththeline.AseriesvariableresistorcanbeinsertedintheDCgridtodirectlymodifytheresistanceoftheline.Itallowstoapplyonlypositivevoltagewhichreducesthecurrentthroughthatcable.Itsmaindisadvantageisthatthelossesofthesystemgetincreasedandmayrequireadditionalcoolingequipment[24],though,itssimplicityisakeyfactortotakeintoaccount.AschemeoftheseriesvariableresistorisshowninFig.3. SimilartechniqueshavebeenappliedinACsystemsforfaultride-throughofwindturbines[25].

AC-DC converters exchange power between the AC systemandtheHVDCgrid.Therefore,theyapplypositiveornegativevoltage in series with the line where they are connected andthisallowstoregulatethecurrentflow.Thevoltageapplied dependsontheexternalACsourceandtheconverter topology.Anisolationtransformerisrequiredtobefloatingatthepositive pole or the negative pole, so that the device does notneed to withstand the nominal voltage of the DC system, butonlyasmall Several topologies of AC-DC converters for power flowcontrol have been proposed in the literature. An AC-DC con-trollermadeoftwosix-pulsesthyristorconvertersconnectedindual-configurationispresentedin[26].Itallowsfour-quadrant operation active and reactivepower independently. The advantages lie in the simplicity andreliabilityofthyristorconvertersandtheirlowlosses.Fig.4(a)depictstheschemeofthethyristor-basedCFC

Another proposal regarding AC-DC converters for powerflow is the concept introduced in [27], [28]. The converter isshowninFig.4(b)andismadeofatwo-level,threephaseVSCanda four-quadrantchopper.Thetwo-level VSCmaintainsthecapacitorvoltageAC side.Nevertheless, converter losses can be higher in comparisonwith the thyristor-based converter [26]. In [29], an analogousAC-DC converter but based on modular multilevel currentsourcetechnology[30]ispresented.

DC-DC converters based CFCs exchange power betweendifferent lines of the HVDC system, thus they are also called*interline*CFCscompaHrison with the

AC-DCconverters,thevariablevoltagetheycanapply islimitedbytheHVDClinecurrentsandtheconvertertopology.Theyarealso floating at the HVDC poles and the power extracted from onelineisinjectedintotheotherline,applyingpositivevoltagein one line and negative voltage in the other line if currentsflowshavethesamedirection.

One of the first DC-DC converters for current flow controlwasproposedin[32],[33].Itconsistsontwo H-bridges,each one connected to one HVDC line. Fig. 5(a) shows thepresentedtopology,whichwaschosentotakTe advantageofthestandard VSC full bridge cell [32]. An alternative topologywith the same functionality is depicted in Fig. 5(b), whichconsistsonmergingthetwocapacitorsandremovingtheredundant switches. It allows to apply positive or negativevoltage in any line, and it is prepared to operate with anycurrentflowthroughthelines.Thecapacitoris usedtoexchange power between the two HVDC lines. This converteris analysed in [34], [35]. In [36], an experimental validation ofthisCFCtopologyisalsoprovidedalongwiththecoordinationandcontroloftwooftheseconvertersinthesameHVDCgrid.

AnotherproposalofaninterlineDC-DCconverterforpower flow regulation is presented in [31]. Although this converter ismade of two H-bridges as well, their switches require reverse-voltage blocking capability since capacitor vJKoltages can bepositive or negative. Introducing a diode in series with eachIGBTisoneoptiontoachievesuchcapability. Thisdevicealsoallows to operate with any current flow. The element whichexchangespowerwiththetwoH-bridgesisaninductance(made of an inductance plus an isolation transformer), insteadof the capacitor used in [32]. The general topology scheme isdepictedinFig.6(a).

When considering a 3-terminal meshed DC grid, the previ-ous topology can be simplified into Fig. 6(b). This convertertopology is rather simple but it allows to operate only whenline currents are entering the CFC, so that the MMC-VSC inFig.6(b)isactingasaninverter

III. VISION OF COMPLEX HVDC GRIDS INCLUDING FLEXIBLE DC-DC CONVERTERS

Time horizon	HighvoltageACsystems	HighvoltageDCsystems
Nowadays	Dominatethepowersys-tem.ACisthebaseofthe power system, integrat-ing an increasing amount ofpower converters. The keyadvantageofcheap,effi-cient and reliable transform-ersandprotectionsmakeACt hepreferredchoice.	Usedmainlyinpoint-to-point interconnections whenAClinesarenotfeasible (verylongoverheadlines,long cables or connection ofasynchronoussystems).
5 years horizon	TotalintegrationofACand DCtransmissionsystemsinterconnectedinmultiplelocations.Developmentofoffshore AC hubs, intercon-nectedwithHVDCsystems.	Expectedproliferationofmultiterminal VSC-HVDCschemesinterconnectingdifferentHVDCsystems.
15yearshorizon	Possible irruption of solid-statetransformers,movingto ward a pure power elec-tronicsACsystem.	Expectedproliferation of meshed HVDC systems, in-cludingDC-DCconvertersof different types. Possibledevelopment of continentalSupergrids.
Longtermhorizon	Possible segmentationof AC networks, interconnected with convertersandHVDClines.	Possible evolution of thenetworktoaglobalinter-continentalHVDCgrid,makingpossibleinterconnection of differentcontinents.

The different control approaches investigated in the last years [1], [2] have addressed the need to control the voltages and powers throughout meshed HVDC grids. However, most studies assume the usual shunt connection of the converters and therefore, the studies are not considering the possibility of using series-connected converters to further improve the system performance, especially in the case of risk of overload of some of the system lines. In practice, such overloads can cause bottlenecks in the system which can limit the power exchange capability between systems, with the consequent economic impact, when the interconnected systems have im- portant differences in the cost of electrical energy.

A. Flexible converters for meshed HVDC grids

Series-connected CFCs can evolve to become a new breed of power converters to ensure a high flexibility in HVDC grids.

controls to mitigate potential unstable oscillation modes.

The converter principle of operation (for most of the in- terline concepts) relies on inserting the capacitor alternatively in one or the other line, allowing the converter to act as two variable DC sources connected between lines. This equivalent variable DC sources allow changing the system voltages and therefore modifying the overall system power flow and allowing an enhanced system controllability. The converter has a reduced amount of energy storage (only in the DC capacitor) which can be adjusted choosing the right capacitor. In order to provide the system services (Bpower flow control capability, stability improvement, oscillation damping, pole balancing and voltage control), the converter applies the right voltage in the voltage sources and therefore changes the overall system currents and voltages. The concept can be understood as having series FACTS (Flexible AC Transmission Systems) in DC networks, with the key difference than in DC systems reactive power is meaningless. Some of the AC-DC converters of the system (MMC based VSC-HVDC) will also have capability of providing ancillary services to the hybrid HVDC grid. These converters will be coordinated with the flexible DC-DC converters to provide the required services. The series disposition of the converters allows to provide some of the services more efficiently as they can impact more importantly the overall system power flows.

The possible integration of DC-DC converters with DC circuit breakers is especially significant, to develop a device with advanced functionalities while minimizing the cost.

B. Future complex HVDC grids

The following five concepts (Fig. 12) show some possible evolutions of HVDC transmission systems for offshore wind power plants. The baseline case is Concept 0, which is a point-to-point VSC-HVDC transmission link. Some of the concepts discussed are natural evolutions which hTGDGFDHave been already investigated while others are more disruptive concepts:

• Concept 1: Multiterminal HVDC system. This is the natural evolution of point-to-point systems (Concept 0).

• Concept 2: Converter stations with reduced cost. Different technologies have been suggested for cost reduction of offshore converter stations. These include diode-rectifer based converters, LCC converters, DC collection grids for the offshore wind power plant, and others. Some of the concepts can potentially achieve cost reduction, also rising some technical challenges on the overall system controllability, operation and protection.

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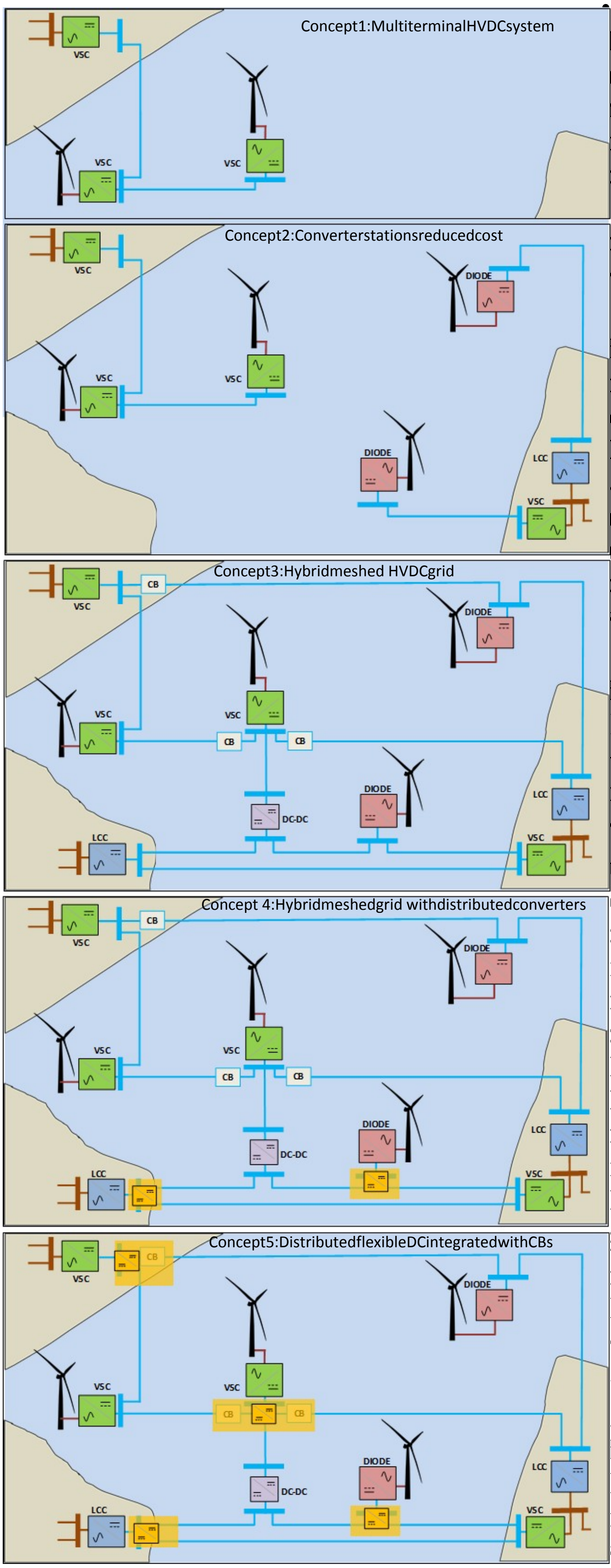

Figure 12. Possible evolutions of HVDC transmission systems for offshore wind power plants

Concept 3: Hybrid meshed HVDC grid. The cost reduc- tion of the converter stations and the evolution towards a meshed HVDC network are combined, resulting in a complex hybrid system including converters of different nature. Circuit breakers are also required to define dif- ferent protection zones and avoid in whole system loss whenever a fault in the DC grid occurs.

Concept 4: Hybrid meshed grid with distributed convert- ers. Flexible DC-DC converters (of low cost, because of their lower power rating) are proposed. Flexible DC-DC converters will be used for multiple services including power flow control, ancillary services for the HVDC grid or adjacent grids, stability improvement, oscillation damping, pole balancing and voltage control.

Concept 5: Hybrid meshed grid with distributed flexi- ble DC-DC converters and flexible DC-DC converters integrated with HVDC circuit breakers. The concept of integration of flexible DC-DC converters with HVDC circuit

t for power exchange between countries and to increase the reliability of the transmission of offshore generated power. Concept 3 is likely to be unstable (for the lack of controllability), and therefore Concept 4 is proposed at the cost of increasing the CAPEX by adding the proposed flexible DC-DC converters. This CAPEX increase is compensated by the OPEX reduction for the improved system reliability and availability. Concept

5 integrates the flexible DC-DC converters converters with HVDC circuit breakers, and therefore it achieves OPEX im- provement without increasing the CAPEX.

It is important to remark that while Figure 12 covers a complex HVDC grid with different technologies of power converters, the proposed converter will be also needed in different possible scenarios with less variability of power electronics converters.

Fig. 13 shows an example of an eventual future European HVDC grid including multiple different technologies in the converter stations (Concept 3). The illustrated concept does not pretend to show the best possible future solution, but to exemplify a possible hybridized network that can eventually exist as a result of a complex history of decisions taken by several transmission system operators, regulatory bodies, offshore renewable projects developers and HVDC technology providers. The upper subfigure includes a network divided into 5 different protection zones (to minimize the number of HVDC circuit breakers) including LCC-HVDC, VSC-HVDC and DC-DC converters The different circled numbers in Fig. 13, indicate the different protection zones). In such a highly hybridized4 and 5) to deal with the control of the overall power flows and maintain the system stability. The proposed converters are small power converters connected in series used to control the power flows, ensure the operation at the reference voltage, damp oscillations, while ensuring proper operation in normal and fault conditions (for faults in the DC and AC systems). The converter is integrated in some cases with one or several circuit breakers. It can be noticed that power converters with multiple output channels will be required.

HVDC	HVAC	LCCAC-DC	VSCAC-DC
DC-DC converter	HVDCDC Breaker	FlexibleDC/DCconverter	Protectionzone n

Figure 13. Example of a possible future European HVDC grid

IV. FLEXIBLE DC-DC CONVERTERS FOR HVDC GRIDS

The following features characterize the proposed concept:

1) Small: Converters will be rated at full line current, but rated to limited voltage, approximately 1-5% of the HVDC rated voltage. Therefore, the device rated power will be of 1-5%.

2) Multifunctional: Converters will provide a range of functionalities, including power flow control capabil- ity, ancillary services for the HVDC grid or adjacent grids, stability improvement, oscillation damping, pole

balancing and voltage control. The converters can help to mitigate possible perturbations or oscillations caused by specific power converter solutions in the AC-DC converter stations.

3) Distributed: A number of devices will be installed in the network in order to guarantee an optimal system operation and maximize efficiency and reliability.

4) Integrated: The converter will be integrated with HVDC circuit breakers. This will allow a multifunctional cir- cuit breaker, combining the functionalities of the two devices.

5) Secure: As it is not a protection device, the converter needs to be protected or integrated (previous point) by other elements of the system. The converter will have to be coordinated with appropriate circuit breakers to ensure the safe operation. The converter will include a bypass which will be activated when the converter is not operating and it can also be used in fault condition.

6) Efficient: Due to the reduced power rating of the con- verters, the losses are expected to be also low. In [32], the losses of the Dual H-bridge CFC are stated to be around 24 kW and in [57], for the converter in Fig. 21(a), are calculated to be between 8-23 kW, depending on the operational point. In both cases the converters are steering hundreds of MW.

7) Reliable: The converter complexity is reduced, due to the rating of 1-5% of the HVDC voltage. For instance, the CFC device presented in [32] is thought to be made of two MMC full bridge cells and other works consider a reduced number of switches in series to withstand the re- quired voltage [39]. While expected failure rates are very low, as it is a series-connected converter, it is needed to employ a bypass switch which will be activated in case of any failure in the converter. The distributed concept, discussed in Subsection IV-B, contributes significantly to improve the reliability of the concept as a number of

devices are introduced in the system and some of them can be used to provide a similar service in case of failure, bringing extra redundancy.

In the rest of the Section, some research results and ideas are exposed in order to enhance the presented features.

A. Small series connected interline converters

The converters can be considered small because they have power rating which is a small fraction of the power they are handling (1 to 5 % as example). This Section shows the sim- ulation and experimental results of the interline DC-DC CFC [39], [40] illustrated in Fig. 8(a). The operation of the device consists on inserting a capacitor in series with the lines where it is connected by closing its switches in a complementary manner. The current of the lines can be regulated based on the previous operation and the CFC capacitor achieves a certain voltage that ensures the desired current relation. Also, the duty cycle sent to the switches establishes the current relation in steady-state [39].

V. TRENDS, CHALLENGES AND RESEARCH NEEDS

The research and development activity related to flexible DC-DC converters for HVDC grids is very linked to the feasibility of HVDC grids and Supergrids. Several studies conducted worldwide [64]–[66] support the development of HVDC grids. The development of the projects has to face important technical and non-technical barriers and there is uncertainty on how this will be conducted in the next years. Researchers from both industry and acamdemia are exploring different power electronics, protection, cable, operation and control aspects related to Supergrids. As far as flexible DC- DC converters are concerned, several researchers are working on different power electronics concepts (presented in the State of the Art Section) and analyzing the system benefits of using such converters. It is worth remarking, that it is very likely that the development of these converters will be very related to the emergence of active circuit breakers, capable not only of breaking currents, but also providing the functionalities described in the paper. The main benefit of integration is that the functionalities of flexible DC-DC converters would come ”for free” with two adjacent circuit breakers.

Another important trend is the study of hybrid HVDC grids using both VSC and LCC converter technologies. Hybrid configurations combine low costs and power losses from LCCs

terminal DC grid is planned to be commissioned in 2019 [71]. This system is based on an LCC operating as rectifier and two VSCs operating as inverters and is rated to 8 GW at ±800 kV. The main challenges related to the development of flexible DC-DC converters for HVDC grids can be summarized as

follows:

- System interactions. HVDC grids have almost no inertia and multiple power electronics converters controlled by different algorithms implemented by different manufac- turers. New types of oscillations and interactions are likely to occur and can challenge the practical implemen- tation of such systems.
- Reliability enhancement. Power electronics systems are more and more reliable, but there is still uncertainty which needs to be clarified. It is fundamental to ensure that flexible DC-DC converters are extremely reliable and do not cause any problem in the system where they are installed.
- Cost. Adding equipment in a system which is already very expensive is an important challenge. While the cost of the proposed converters is low compared to MMC or circuit breakers, the option of integrating them with other equipment seems more appropriate to face this challenge.
- Integration of the proposed converters with hybrid LCC- VSC schemes. Flexible DC-DC converters can provide functionalities which are very relevant for hybrid systems, which are significantly

constrained (limited controlla- bility, higher harmonic distortion, risk of commutation failure, etc.)

Significant research is required in the field to allow further development of flexible DC-DC converters for HVDC grids. The suggested research needs can be organized as follows:

• Power electronics: While there are several relevant con- cepts proposed, there is room for development of new enhanced converter topologies.

• Usage of modern advanced materials for the power semi- conductors and for the converter passive components (ca- pacitors and inductances). Wide bandgap semiconductors (including silicon carbide and gallium nitride) can be used in order to enhance the converter efficiency and reliability.

• Converter integration for cables and lines of different technologies.

• Power system protection: It is important to investigate different protection options to ensure the safe converter operation at a minimum additional cost. While integration with circuit breakers is a sound option, other alternatives can make sense for some applications.

• Functionalities implementation: Several studies have ad- dressed the power flow control functionality, but therelimited research on how to achieve other functionalities described in the paper, like oscillation damping, pole balancing, and ancillary services provision.

• Integration of the proposed converters in existing overall voltage and power control schemes. While the proposed converter can provide some functionalities described in the paper, it will also impact the overall system power flows and voltage controls. Further research is needed to investigate optimal approaches to integrate the converter operation modes with existing overall system controllers.

• Operation and economical analysis: Simplified models of the converters need to be developed and integrated in power flow, optimal power flow and security constrained optimal power flow studies. Such studies can reveal the economical benefits of employing the converters. The development of cost models is also fundamental to analyze the economic viability of the concept.

• Integration: Integration with circuit breakers or MMC of different technologies can be further explored. Integration in hybrid LCC/VSC systems.

• Control interactions analysis: System studies considering complex systems including the proposed converters need to be studied to better understand the overall system interactions and the services that can be provided by the converter.

I. CONCLUSION

The paper has addressed the concept of flexible DC-DC converters for complex HVDC grids. The deployment of complex HVDC grids can trigger some challenges related to the overall system stability and control. Flexible DC-DC converters can directly control current and power in the lines, while providing several functionalities to the HVDC grid, including power flow control capability, ancillary services for the HVDC grid or adjacent grids, stability improvement, oscillation damping, pole balancing and voltage control.

The paper has summarized some advances on the proposed technology, including power electronics technical concepts, converter operation and control functionalities and integration with circuit breakers. The paper has presented the main features expected of flexible DC-DC converters (small, mul- tifunctional, distributed, integrated, secure, efficient, reliable) and has formulated a possible vision on future complex HVDC grids.

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