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An Initial Topology of Multi-terminal HVDC Transmission System in Europe: A Case Study of the North-Sea Region

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***Abstract*—In this paper, technical challenges for realizing offshore multi-terminal HVDC (MTDC) transmission system in Europe is evaluated. An offshore MTDC topology is projected by interconnecting point-to-point HVDC links with the same voltage level and technology found in south-eastern part of North Sea. Availability analysis is done to evaluate the feasibility of the proposed offshore MTDC topology. As compared to point-to-point (PtP) HVDC link, MTDC operation gives a more secure and reliable system. This paper shows that the proposed MTDC topology can operate 98.36% of the time.**

***Index Terms*—HVDC transmission, line commutated converter (LCC), multi-terminal DC (MTDC), voltage-sourced converter (VSC)**

I. INTRODUCTION

Europe is the central point of offshore wind power deployment by having more than 91% of global offshore wind power [1], [2]. Among European regions, the North Sea has become the most utilized region in which 6 out of 10 Europe's offshore wind turbines are installed. Furthermore, the European Network of Transmission System Operators for Electricity (ENTSO-E) estimated that by 2020 there will be more than 25 GW offshore wind power installed in North Sea [3].

There are two different ways to transmit wind power from offshore to the mainland, i.e. high voltage AC (HVAC) or DC (HVDC) submarine cables. HVAC approach has been used for connecting several offshore wind farms, e.g., London Array and Horns Rev 1 & 2. However, HVAC approach suffers from increasing losses for longer distance transmission. HVDC approach offers lower losses for long distances but higher investment cost as compared to HVAC. The break-even distance between HVDC and HVAC for offshore power transmission may vary from 60 to 100 km [4]–[6].

In term of HVDC technology, voltage-sourced converter (VSC) has more advantages as compared to line commutated converter (LCC) in its ability to support passive network, decoupled bidirectional active and reactive power control, and less filter requirement which in turn reduces the converter station size. However, LCC-based HVDC is a mature technology and still favorable in transmitting power over long distance and high level power with lower converter losses as compared to VSC-based HVDC.

Apart for connecting wind farms to mainland, HVDC link is also used for electric power interconnection between countries which opens up shore-to-shore electricity trading. As an example is Skagerrak 1-4 that helps Denmark to be less dependent on coal-fired power house by importing hydro electric power from Norway during low wind condition in Denmark. For the same environmental purpose, another application of HVDC link in North Sea is for powering offshore oil/gas platforms (e.g. Troll A and Valhall in Norway), i.e. onshore hydro electric power is used to replace the utilization of natural gas for electricity in the platforms which in turn reduce CO2 emission.

In the North-Sea region today, 15 point-to-point (PtP) HVDC links are already in operation while at least 10 more links are being planned or under construction and anticipated to be commissioned by 2020. The south-eastern part of the North-Sea region is the most dense part by hosting 12 links as shown in Figure 1 (their data is given in Table I).

DC interconnection forming multi-terminal HVDC (MTDC) transmission systems provide significant improvement in flexibility, security of supply and utilization of transmission links as compared to PtP transmission systems [7]. Furthermore, it is envisioned by CIGRÉ as the first step towards fully-meshed DC grids, MTDC operation can be formed as radial network by interconnecting neighboring HVDC links or connecting a new converter into existing DC system [8].

Until now, offshore MTDC is not yet realized in Europe. Several designs of offshore MTDC transmission systems in North Sea have been proposed [9], [10]. Previous proposals were discussed and compared in [11]. Furthermore, at the end of 2010, 10 North Sea countries have signed a Memorandum of Understanding to form the North Sea Countries' Offshore Grid Initiative (NSCOGI) [12]. Several studies following this initiative have also been performed to evaluate the design of future North Sea DC grids [13]–[15]. However, interconnection of existing HVDC links has not yet been fully covered. This paper aims to propose a MTDC topology by interconnecting several links found in the south-eastern part

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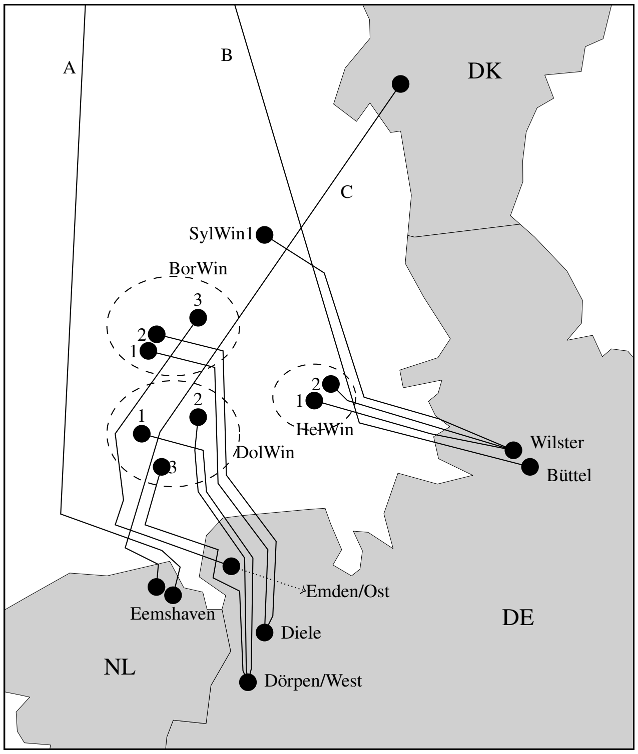

Figure 1. Expected condition of HVDC links in south-eastern part of the North Sea by the end of 2020. NorNed, NordLink and COBRAcable are indicated by A, B and C respectively. Each offshore wind connection link has its own onshore converter station even if more than one link ends are located in the same area (represented by a single dot), e.g. Wilster, Diele and Dörpen/West.

Table I
HVDC LINKS DATA LOCATED IN THE SOUTH-EASTERN PART OF NORTH SEA.

Name	Country	Length (km)	Power (MW)	Volt (kV)	Year	Type
NorNed	NL-NO	580	700	±450	2009	LCC
BorWin1	DE	200	400	±150	2012	VSC
DolWin1	DE	165	800	±320	2015	VSC
BorWin2	DE	200	800	±300	2015	VSC
SylWin1	DE	205	864	±320	2015	VSC
HelWin1	DE	130	576	±250	2015	VSC
HelWin2	DE	130	690	±320	2015	VSC
DolWin2	DE	135	900	±320	2016	VSC
DolWin3	DE	160	900	±320	2017	VSC
BorWin3	DE	200	900	±320	2019	VSC
COBRAcable	DK-NL	350	700	±320	2019	VSC
NordLink	DE-NO	623	1400	±525	2020	VSC

of North Sea. Several technical challenges that hinder the implementation of offshore MTDC transmission system are evaluated in section II. The proposed initial MTDC topology is then discussed in section III. Benefits of MTDC operation as compared to PtP link are addressed in section IV.

II. TECHNICAL CHALLENGES OF OFFSHORE MTDC

Technical limitations of MTDC have been described in [16], e.g. ratings; standards and interoperability; connection to the AC system; protection and grounding; and communication system. Due to the recent MTDC technology advancements and by focusing on the interconnection of several HVDC links, these technical limitations need to be revised.

Some of these limitations, such as MTDC transmission ratings as compared to AC transmission system and reinforcement in the AC network are only apply when there is a need to install/upgrade the existing HVDC link. The impact of HVDC link to the AC network should have been evaluated during planning and preparation phase of the HVDC link installation. Furthermore, during early development stage of the link several studies are also performed in order to decide the size and ratings of the HVDC equipment [17].

In term of protection strategy, a DC fault in PtP HVDC connection will cause an outage of the entire HVDC link. This is not expected in the MTDC transmission system operation since the DC protection system should be able to isolate the faulty line and to ensure continuous operation of system. Interrupting a DC fault current is a complex task because it does not have zero crossing as same as in the AC current and the rise time of the DC fault current is considerably fast. A number of DC breaker technologies used to isolate DC fault have been proposed and comparison of these technologies is presented in [18], [19]. Moreover, several manufacturers have already developed a high speed hybrid DC circuit breaker which is promising for the implementation in MTDC operation [7]. Some examples of protection scheme for meshed MTDC transmission system are proposed in [20], [21].

A step forward towards standardized DC grids control has also been started. A hierarchical control scheme for MTDC has been defined in [8], [22]–[24]. In the hierarchical control scheme, DC grids control is divided into three levels, i.e. local converter station control (primary control), common DC grid control (secondary control), and AC-DC system centralized control (tertiary control). These levels define the response time for each control, e.g. primary control has a response time typically a few milliseconds, secondary control has higher response time ranging from a few seconds until a few minutes and the response time for tertiary control ranging between 5 to 15 minutes. Primary control is expected to be autonomous, i.e. no communication required between converters, while secondary and tertiary controls are centralized. Furthermore, several CIGRÉ working groups have been formed within the HVDC grids area in order to initiate the standardization of DC grids operation, e.g. B4-56: Guidelines for the preparation of grid codes for HVDC Grids, B4-58: Devices for load flow control and methodologies for direct voltage control in a meshed HVDC Grid and B4/B5-59: Control and Protection of HVDC Grids [8].

Beside the good news mentioned earlier, there are still remaining technical challenges for MTDC, i.e. MTDC system voltage rating and combined operation of different converter technologies.

Once the system voltage level is decided for the operation of MTDC system, all of the equipments connected to the system must be rated on this standard. In AC system, several voltage levels can be used in the same system since voltage can be easily transformed from one level to another. In DC system, DC-DC converter which requires such a complex power electronics, is needed for the same purpose. The main drawback of DC-DC converter is the operational losses which is proportional to the voltage difference [25].

Interconnection between LCC- and VSC-based HVDC converters (known as a hybrid operation) has been introduced in order to combine the merits of both technologies, e.g. DC fault current handling [26]. However, since there is a fundamental different in power reversal operation of LCC- and VSC-based HVDC, a bidirectional DC-DC converter is needed as the interface between them [27].

Since offshore platform space is limited and DC-DC converter is predicted to be available after 2025 [7], the first offshore MTDC transmission system is expected to be formed by interconnecting several converters already having the same voltage level and technology to avoid the use of DC-DC converter.

III. AN INITIAL OFFSHORE MTDC TOPOLOGY

Based on the data given in Table I, the dominant voltage level is ±320 kV. This voltage is then used as the standard voltage level for the proposed MTDC topology. Furthermore, all converters with voltage level of ±320 kV are using the same HVDC technology, i.e. VSC-HVDC. By considering the estimated route of each HVDC links (as illustrated in Figure 1), the possible interconnection points for MTDC operation are listed in Table II.

Table II
POSSIBLE INTERCONNECTION POINTS (✓) OF MTDC TRANSMISSION SYSTEM IN THE SOUTH-EASTERN PART OF NORTH SEA.

	SylWin1	*DolWin1*	*DolWin2*	*DolWin3*	*BorWin3*
COBRAcable	✓	✓	✓	✓	✓
DolWin2	-	✓	N/A	-	-
DolWin3	-	✓	✓	N/A	-
BorWin3	-	✓	-	✓	N/A
HelWin2	✓	-	-	-	-

As can be seen in Table II, COBRAcable becomes the only shore-to-shore link available for MTDC operation and has the most interconnection points along its link, e.g. with DolWin1, DolWin2, DolWin3, BorWin3 and SylWin1 links. Moreover, this interconnection between COBRAcable and other offshore HVDC links suits well with the development plan of COBRAcable, i.e. COBRAcable is expected to operate in MTDC at later stage by connecting more converters to its link [28].

Since some offshore wind farm converter stations (e.g.: DolWin1, DolWin2 and DolWin3 offshore stations) are located near to each other (less than 20 km) and the cost of cable including its installation for short distance is way cheaper than building an offshore platform needed to store apparatus such as DC busbars and DC circuit breakers [29], a common interconnection point/hub is more preferable than individual one.

The first DC interconnection hub (Hub1) is then assumed to be located in the crossing route of Dolwin1 with COBRAcable and held the interconnection between COBRAcable, DolWin1, DolWin2 and DolWin3. Furthermore, in order to avoid an extra offshore platform, BorWin3 is also connected with this hub.

Two other interconnection hubs (Hub2 and Hub3) are assumed to be installed in the crossing route between Sylwin1 with COBRAcable and Sylwin1 with HelWin2. Figure 2 illustrates the proposed topology of MTDC which consists of 6 offshore and 8 onshore HVDC stations with 3 offshore interconnection hubs.

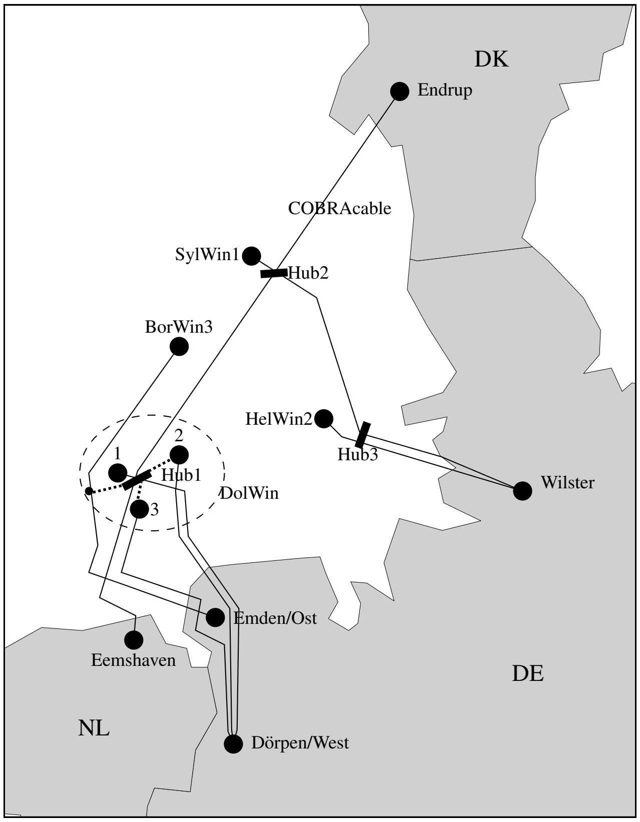

Figure 2. The proposed MTDC topology. The interconnection hubs are represented by rectangular boxes. The dotted line represent the extra cables needed for interconnection.

IV. BENEFITS OF MTDC TRANSMISSION SYSTEM

The proposed MTDC topology can be used to strengthen the interconnection between Denmark, Germany and the Netherlands by allowing exchange of electric power from different directions. During surplus of energy in the Netherlands, 700 MW power can be transported either to the northern part of Germany (via Wilster) or Denmark. Vice versa, when surplus is in Denmark side, the extra power can be transmitted either to the Netherlands or Germany (via Dörpen/West or Emden/Ost). Futhermore, both COBRAcable converters provide alternative route to evacuate offshore wind power during power generation surplus in German network.

MTDC transmission system is also expected to be more secure and reliable as compared to PtP HVDC connection. Figure 3 depicts typical diagram of a VSC-HVDC station which consists of AC gas insulated switchgear (GIS), transformer, converter reactor, converter valves, DC filters and DC switchyard. In PtP connection, two converter stations are connected with DC cable in between. A failure in either of these converter station components or DC cable can result in an outage of the whole system. In MTDC transmission system, the failure can be localized and the healthy part of the system can continue to supply the costumer.

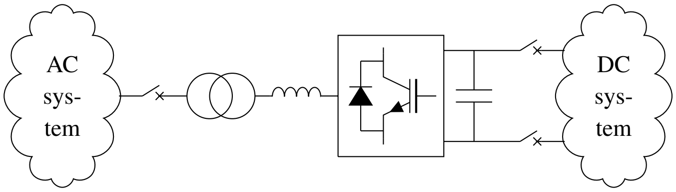

Figure 3. Example of one symmetric monopole VSC-HVDC converter station.

In order to assess the improvement of system availability from PtP into MTDC transmission system, one should know the availability index of each component that build up the system. Availability index of a component can be calculated as:

$$A = \frac{MTTF}{MTTF + MTTR} \tag{1}$$

where A is the availability index, MTTF is the mean time to failure and MTTR is the mean time to repair. Reliability indices of the VSC-HVDC converter station components is given in Table III. In general, the difference between offshore and onshore components is the repair time because it needs more time to access offshore platform [30]. It is assumed that all VSC-HVDC listed in Table II are of symmetric monopole with modular multilevel converter (MMC) scheme.

Table III
VSC-HVDC CONVERTER STATION COMPONENTS RELIABILITY INDICES [30].

Location	Component	MTTF (yr)	MTTR (hr)	Availability
Offshore	GIS (275 kV)	250.00	184.00	0.99992
	Transformer	95.00	1512.00	0.99819
	Reactor	7.00	192.00	0.99688
	MMC valves	1.90	60.00	0.99641
	Control system	1.60	17.00	0.99879
	DC switchyard	4.02	98.06	0.99722
Onshore	GIS (400 kV)	100.00	120.00	0.99986
	Transformer	95.00	1008.00	0.99879
	Reactor	7.00	24.00	0.99961
	MMC valves	1.90	12.00	0.99928
	Control system	1.60	3.00	0.99979
	DC switchyard	4.02	26.06	0.99926

In PtP link, two converter stations and DC line are connected in series. Therefore, the availability for PtP link can be calculated by multiplying all of these components together. The failure rate of a 100 km submarine DC cable equals to 0.07 occurrence/yr with the repair time equals 60 days [30], [31]. The availability of the underground DC cable is expected to be higher, i.e. faster repair time. However, since the reliability data of underground DC cable is not available, in this paper it is assumed that all cables are installed under sea. The availability index for each PtP links are then given in Table IV.

Table IV
AVAILABILITY OF PTP VSC-HVDC LINKS.

Name	Length (km)	Availability
COBRAcable	350	0.95320
DolWin1	165	0.96541
DolWin2	135	0.97777
DolWin3	160	0.97491
BorWin3	200	0.97034
SylWin1	205	0.96977
HelWin2	130	0.97834

In this paper, the failure rate of the cable is assumed to be proportional with the distance. This assumption might not be fully true since the availability of the cable depends on many aspects, e.g. the burial depth, activity around the cable route and laying conditions. Therefore, Table V shows the sensitivity of DC cable reliability to the overall system availability. As can be seen in Table V, the increase in failure rate of cable is much more severe for the availability of PtP link.

Table V
DC CABLE SENSITIVITY FOR PTP VSC-HVDC LINK.

Cable failure rate (occ./yr/100km)	Availability
0.700	0.59320-0.84463
0.070	0.95320-0.97834
0.007	0.98223-0.99171

In order to calculate the availability index for the proposed MTDC topology, an equivalent system for the series-connected components is used (depicts in Figure 4). An equivalent offshore system (OFS) or onshore system (ONS) consists of a VSC-HVDC station, a DC cable which is required for connecting this station to the interconnection hub and high-speed

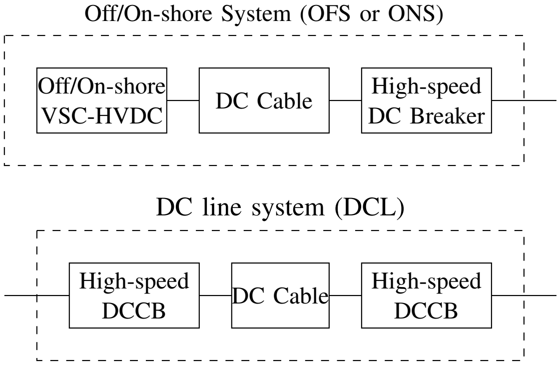

Figure 4. Series components are combined into an equivalent component, e.g. offshore VSC-HVDC system, DC cable and high-speed DC breaker are combined into an offshore system (OFS).

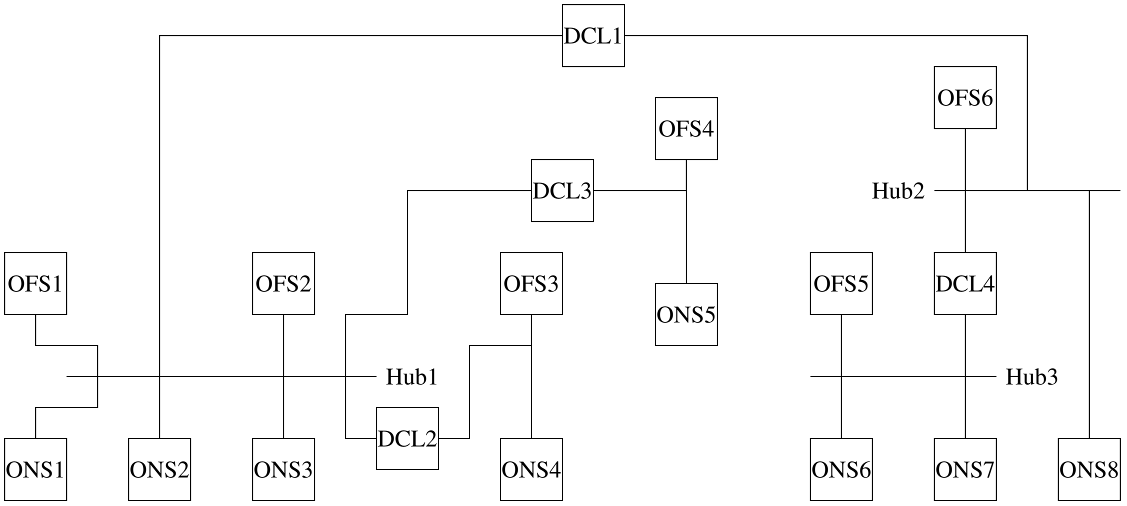

Figure 5. Reliability model of the proposed topology. OFS and ONS represent the offshore and onshore system (as depicted in Figure 4), while DCL represents DC cable. The availability data for each component is given in Table VI

DC circuit breaker (DCCB) located in the interconnection hub. Meanwhile, a DC line system (DCL) represents an equivalent for a DC cable equipped with two high-speed DCCBs at their ends which are used to connect the cable to the interconnection hub. The reliability model of the proposed MTDC topology is then depicted in Figure 5.

Taking MTTF of an offshore high-speed DCCB equals to 20 years and MTTR equals to 180 hours [31], the availability indices for each component depicted in Figure 5 are given in Table VI. There are no DC cables in OFS3 and OFS4 since the DC cable for interconnecting these stations to the interconnection hub are represented separately as DCL2 and DCL3. In DCL2 and DCL3, it is assumed that one DCCB is used to connect the cable to DC switchyard while the other is used to connect to the interconnection hub.

Table VI
AVAILABILITY DATA FOR THE MODEL DEPICTED IN FIGURE 5.

System	Components			Availability
	HVDC station	Cable (km)	No. DCCB	
OFS1	BorWin3	89*	1	0.97635
OFS2	DolWin1	7	1	0.98565
OFS3	DolWin2	-	-	0.98746
OFS4	DolWin3	-	-	0.98746
OFS5	HelWin2	21	1	0.98407
OFS6	SylWin1	12	1	0.98509
DCL1	-	169	2	0.97854
DCL2	-	13	2	0.99646
DCL3	-	6	2	0.99726
DCL4	-	84	2	0.98830
ONS1	BorWin3	137*	1	0.97988
ONS2	COBRAcable	71	1	0.98744
ONS3	DolWin1	158	1	0.97747
ONS4	DolWin2	135	1	0.98010
ONS5	DolWin3	160	1	0.97724
ONS6	HelWin2	109	1	0.98308
ONS7	SylWin1	109	1	0.98308
ONS8	COBRAcable	110	1	0.98297

*includes 13 km cable to connect to the interconnection hub.

Each of the component depicted in Figure 5 can be either available or in outage condition. Therefore, the proposed MTDC topology has 2^{18} possible configurations. In order to calculate the availability of the proposed MTDC topology, the energy availability for each configuration must be calculated first by multiplying the probability of the configuration with the ratio between capacity of the configuration and the full power transfer capacity of the proposed MTDC topology. The availability of the proposed MTDC topology is then retrieved by summing up the energy availability of all these configurations.

The availability index of the proposed MTDC topology for different cable failure rates is given in Table VII. The availability of the proposed MTDC topology is increased 0.5-3% as compared to PtP transmission system. It is also shown in Table VII that the dependency of the DC cable to the overall system availability is reduced.

Table VII
AVAILABILITY OF THE PROPOSED MTDC TOPOLOGY.

Cable failure rate (occ./yr/100km)	Availability
0.700	0.92113
0.070	0.98363
0.007	0.98641

V. CONCLUSION

By 2020, there will be at least 25 HVDC links in operation in the North-Sea region. Hitherto, 10 links are still under development while the rest are already in operation. Among these links, 12 links are located in the south-eastern part of the North-Sea region. Some of these links, e.g. COBRAcable, DolWin1, DolWin2, DolWin3, BorWin3, SylWin1 and HelWin2, are of the same VSC-HVDC scheme and have the same voltage level. Furthermore, the cable route for these links are close to each others which becomes more feasible to interconnect these links to form an offshore MTDC transmission system.

As compared to PtP connection, MTDC transmission system offers a more flexible, secure and reliable operation of the system. In PtP connection, failure of single component in the transmission system leads to overall system shut down, while in MTDC transmission system this failure can be localized without the need to shut down the entire system. Moreover, availability analysis has shown that the proposed offshore MTDC transmission system can operate 98.36% of the time. It is also shown that MTDC transmission system becomes less sensitive to the DC cable availability. However, since the HVDC links in the proposed offshore MTDC system are manufactured by different vendors, another challenge might arise in coordinating between HVDC converter controllers. Further studies are required to develop a connection guidelines for multi-vendor multi-terminal HVDC (MV-MTDC) transmission system.

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