Connection of an offshore wind park to HVDC converter platform without using offshore AC collector platforms

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***Abstract*—Several large scale offshore wind farms are planned to be built far from the shores in the future. High Voltage Direct Current (HVDC) Light by ABB is an effective and reliable way to integrate this large scale wind power production to the grid. An expensive component of offshore wind park HVDC Light technology is offshore AC collector platform. The AC collector platform in the offshore wind farm HVDC link contributes significantly to the cost of the overall project. This paper investigates the comparison between two different AC topologies of an offshore wind farm connection to offshore HVDC converter platforms with and without offshore AC collector platforms. The technical feasibility of the omission of an AC collector platform from offshore wind farms connection to HVDC converter platform is investigated for the first time.**

In the first topology, the offshore wind farms are connected to an HVDC converter platform through offshore AC collector platforms. An offshore AC collector platform is used to collect energy from the wind farm and step up the voltages for transmission to offshore HVDC converter platform. The offshore AC collector platforms contribute significantly to the total cost and technical complexity of the HVDC connection.

In the second topology, the offshore AC collector platform is removed from the circuit and the offshore wind farms are connected directly to offshore HVDC converter platform. The topological alteration of an offshore wind farm HVDC link gives rise to some technical challenges. The short circuit analysis and annual energy loss analysis is performed for these two topologies. The type of wind turbine generators, internal wind farm voltages and the distance between the wind farms and offshore HVDC converter platform are quite important factors that are investigated in this study. The short circuit analysis and loss analysis is performed for two types of wind turbine generators i.e. doubly fed induction generators (DFIG) and full conversion (FC) generators. Two internal wind farm voltage levels i.e. 33 kV and 66 kV, and three different distances i.e. 1 km, 5 km, and 10 km between the wind farms and offshore HVDC converter platform are investigated.

I. Introduction

A rapid boost in the development of offshore wind power has been seen in the recent years. The planners and developers are looking to grab the opportunities offered by the excellent wind resources far from the shores. It is expected that offshore wind power capacity will reach 75 GW by the end of 2020 [1]. As far as the pilot and small scale offshore wind power plants are concerned, traditional high voltage alternating current (HVAC) is an economical option to transmit energy to onshore grids but larger capacity and increased distance from the shore makes it technically and economically difficult to connect offshore wind parks to the land grids. HVDC emerges as a viable option for such applications. HVDC Light, provided by ABB, proving ideal to bring power to the shore and to assure good power quality [2]. Still the cost of an offshore HVDC connection needs to be reduced to make it economically more feasible. The offshore AC collector platforms contribute significantly to the total cost of an offshore HVDC connection of large wind parks. The exclusion of offshore AC collector platforms from the HVDC link can reduce the overall cost of the project but technical complexity of the project might increase which will be addressed for the first time in this paper to the best of our knowledge.

The main purpose of this study is to compare the two topologies of an offshore wind farm cluster connection to the HVDC converter platform. An HVDC connection from an offshore wind farm to the onshore grid mainly consists of two platforms i.e. ac collector platform and HVDC converter platform. In this thesis, three hypothetical wind farms i.e. A, B and C having power capacity 402 MW, 252 MW and 150 MW are selected respectively.

In the first case, the 804 MW offshore wind farm cluster will be connected to an offshore HVDC converter platform using AC collector platforms. The internal voltage level of the wind farms will be kept at 33 kV. The short circuit analysis and loss analysis will be performed for two kinds of wind turbine generators i.e. DFIG and FC generators.

In the second case, the 804 MW offshore wind farm cluster will be connected to an offshore HVDC converter platform without using the offshore AC collector platforms. The short circuit analysis and loss analysis will be performed for two wind turbine generator types i.e. DFIG and FC generator. Further in this case, the effect of changing the distance between wind farms and offshore HVDC platform on short circuit currents will be observed. Also, two internal voltage levels i.e. 33 kV and 66 kV of the wind farms will be

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compared for short circuit currents in the absence of AC collector platforms. The circuit under consideration starts with the offshore wind farms and ends at offshore HVDC converter platform.

II. Connection Configuration of an Offshore Wind Park to HVDC Converter Platform without using AC Collector Platforms

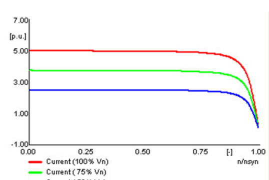
Different configurations were simulated for connection of an offshore wind park to HVDC converter platform with and without AC collector platforms as shown in Figure 2.

A. *Wind Turbine Configuration*

Siemens 6 MW offshore wind turbine model is used for this study. The detailed specifications are in Appendix 2 of reference [3]. Two types of wind turbine generators i.e. DFIG and FC generators are investigated. These are the some of the most common wind turbine generators which are currently being used in the market. The 6 MW DFIG is selected with following specifications:

Specifications	
Apparent Power(MVA)	6.667
Rated Voltage(kV)	0.69
Nominal Frequency(Hz)	50
No. of Pole Pairs	2
Stator Resistance(p.u)	0.01
Stator Reactance(p.u)	0.1
Locked Rotor Current(p.u)	7
X/R Locked Rotor	2.332

TABLE I: Specifications of DFIG from DIgSILENT



(a) (b)

Fig. 1: The torque and current graphs of regular squirrel cage induction generator from DIgSILENT

The full conversion generator chosen for this study is a synchronous generator. The short circuit contribution of full conversion generator is limited to 110% of the rated current both initially and thermally [4]. So synchronous generator model having apparent power 6.667 MVA and rated voltage 0.69 kV is selected. The generator impedance is adjusted iteratively to achieve the desired short circuit current value. For detailed calculation methodology, see Appendix 2 of reference [3]

B. *Cable Connection Specifications*

Two types of cables are used in this study i.e. inner array cables and export cables

1) The inner array cables specifications: The inner array cables connect the individual wind turbines, in each feeder, to AC collector platform of each wind farm. The length of the cable between two wind turbines is kept at 0.9 km. The length of the cable between the wind turbine and offshore AC collector platform is kept at 2.5 km while in the absence of offshore AC collector platform; three different lengths are chosen i.e. 1 km, 5 km and 10 km.

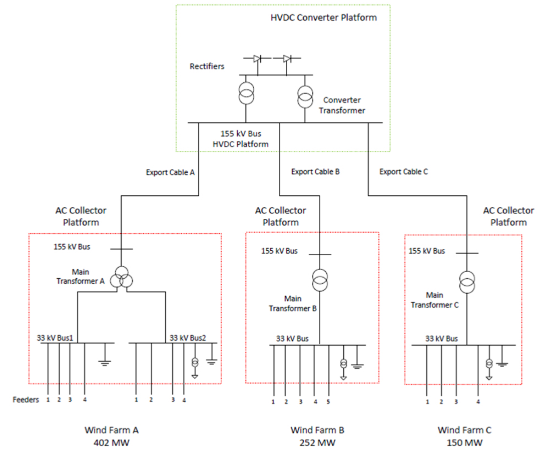
Wind farm A consists of 67 turbines. The internal grid of the offshore wind farm is divided into eight feeders. Three feeders connect nine turbines while five feeders connect eight turbines to the offshore AC collector platform as shown in Figure 2.

Wind farm B consists of 42 turbines. The internal grid of the offshore wind farm is divided into five feeders. Two feeders connect nine turbines while three feeders connect eight turbines to the offshore AC collector platform as shown in Figure 2.

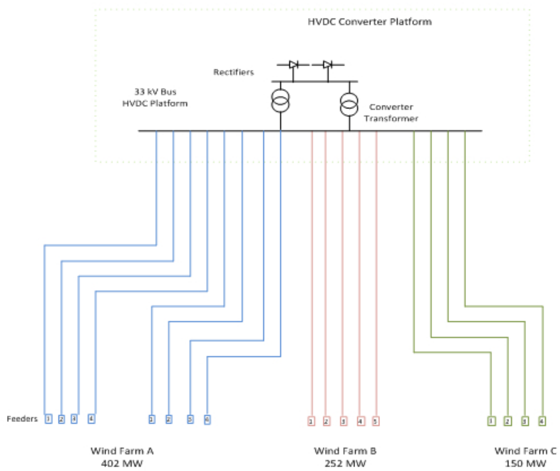
Wind farm C consists of 25 turbines. The internal grid of the offshore wind farm is divided into four feeders. One feeder connects 7 turbines while three feeders connect six turbines to the offshore AC collection platform as shown in Figure 2.

The 33 kV sea cables inside the wind power plant (the inner array cable) are used with two different cable cross sections. Cables from wind turbine 1 to 7 have the cross section of 630 mm^2 and maximum rated current of 0.698 kA. The cables from wind turbine 8 to the offshore AC collector platform have cross section of 1000 mm^2 and maximum rated current of 1.005 kA.

2) The export cable specifications: The export cables, shown in Figure 2, connect the offshore AC collector platform to offshore HVDC converter platform. Three export cables are used to connect three different offshore wind farms to offshore HVDC converter platform. Three different lengths i.e 1 km, 5 km and 10 km is chosen. The export cable which connects AC collector platform of wind farm A to the offshore HVDC converter platform has the cross section of 2500 mm^2 and maximum rated current of 1.712 kA. The export cable which connects the AC collector platform of wind farm B to the offshore HVDC converter platform has the cross section of 2000 mm^2 and maximum rated current of 1.32 kA. The export cable which connects the offshore AC collector platform of wind farm C to the offshore HVDC converter platform has the cross section of 1000 mm^2 and maximum rated current of 1.156 kA. The export cables will be removed when there will be no AC collector platform. For detailed calculation and properties of cables, see Appendix 3 of reference [3]



(a)



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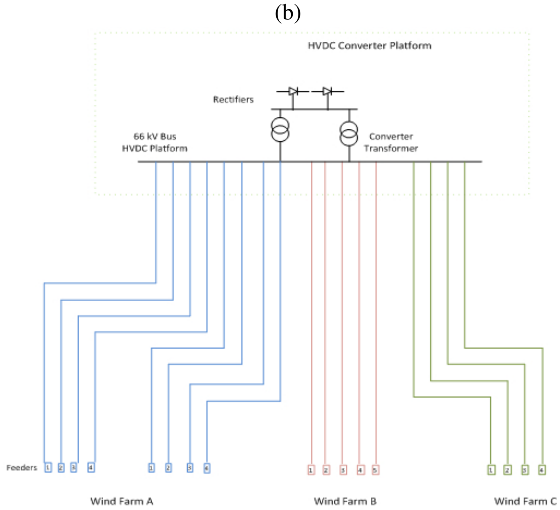


(c)

Fig. 2: Schematic diagram of an offshore wind park connection to HVDC converter platform (a) with AC platforms with 33kV (b) without AC collector platforms with 33kV (c) without AC collector platforms with 66kV

C. *Main Transformer Configuration*

The offshore wind farms are connected to the main transformers placed on offshore AC collector platforms. Each wind farm has its own step up transformer which raises the voltage from 33 kV to 155 kV. The detailed specifications of main transformers are in Appendix 4 of reference [3]. The eight feeders of the offshore wind farm A are connected to a three winding transformer having 444/222/222 MVA capacity and voltage transformation 155/33/33 kV. The five feeders of the offshore wind farm B are connected to a two winding transformer having 280 MVA capacity and voltage transformation 155/33 kV. The four feeders of the offshore wind farm C are connected to a two winding transformer having 170 MVA capacity and voltage transformation 155/33 kV.

III. Technical Analysis for Different Connection Options

In this section, the technical analysis of the offshore wind farms shown in Figure 2 will be presented for losses on yearly basis as well as the short circuit current values. In the first subsection, the losses of wind turbines, cables, transformers, reactive power compensation equipment and offshore AC platform will be investigated for connections having AC collector platforms and connections without AC collector platforms. In the second subsection, the short circuit current values will be analyzed for the same configurations that have been investigated in subsection one. The analysis will be conducted for two types of technologies i.e. DFIG and FC generators. The length of the feeders will varied from 1 km to 10 km between the wind farms and offshore HVDC converter platform for configurations in Figure 2.

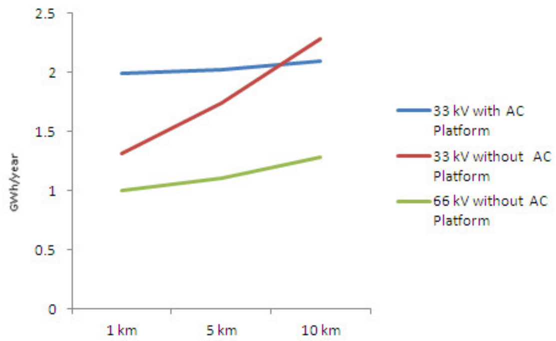
The connection configuration of the test cases was based on an actual HVDC connected offshore wind park in the North Sea. While varying the distances of the feeder connections to the wind farms A, B and C, feeder lengths were taken same for all A, B and C wind farms which is different from the actual scenario. All the simulations were performed using DIgSILENT Power Factory 14.1.

A. *Loss Analysis*

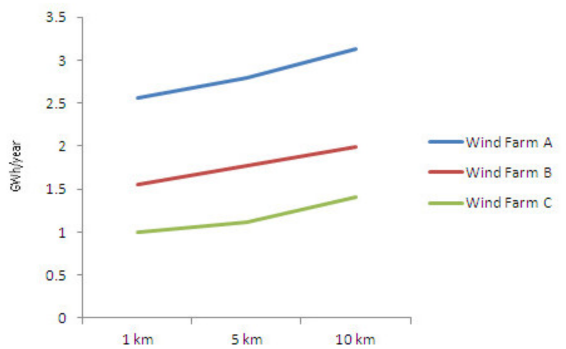
The offshore wind farm connection contains cables, bus bars, transformers, shunt reactors and offshore AC platform which contribute to the electrical losses. A generic DFIG was chosen for loss analysis see Table I and Figure 1.

Following assumptions were made. 70 kW losses are assumed at low loads for shunt reactors having 15 MVAr [3][6]. The capacitor losses can be neglected [3][6]. The zero load losses for main transformers are approximately 0.026% of the apparent power for large transformers and 0.08% of the apparent power for small transformers [3][6]. The offshore AC collector platform losses are considered to be 100 kW [3][6]. The load losses and zero load losses add up to make total losses of the connection.

For loss analysis simulation load flow module in DIgSILENT is employed [6]. To evaluate losses, frequency table



(a)



(b)

Fig. 3: (a) Comparison of the total energy loss (normalized) GWh/year of the offshore wind farm cluster link for different distances between wind farms and HVDC platform (b) Comparison of energy loss (normalized)in GWh/year of three wind farms for different distances between wind farms and HVDC converter platform for 66 kV without AC collector platform

of the wind speed is taken from ABB Sweden in discrete form of 27 points [6]. The full-load time of 8760 hours was taken without taking into consideration the availability since the comparative results are more relevant in this study. The annual energy production and the total losses are calculated based on the wind speed frequency table mentioned above. For detailed results and theory, see Appendix 6 of reference [3]

In Figure 3, it is observed that 33 kV with AC and 33 kV without AC collector platform configurations show that the effects of removing the AC collector platform will be significant on losses for distances less than 10 km. This will improve the losses for less than 10 km for 33 kV without offshore AC platform case. At 10 km this trend is reversed. After 10 km, the 33 kV without offshore AC collector platform case shows increased losses with distances compared to 33 kV with AC platform because the losses in the cables due to the low voltages (33 kV instead of 155 kV) become significantly higher in the absence of offshore AC collector platform. However, 66 kV without AC collector platform shows a relatively slower increase with distance. If we further analyze the losses for 66 kV without AC collector platform case for individual wind farms A, B and C, it is observed that larger capacity wind farms are expected larger impact on losses, see Figure 3(b). It was also observed that the annual energy losses of the topology using 33 kV internal wind farm voltages without AC collector platform are higher than those observed by using 66 kV internal wind farm voltages without AC collector platform.

B. Short Circuit Analysis

The short circuit analysis of the circuit connecting an offshore wind farm cluster to HVDC converter platform is performed. The short circuit currents, during their cycle, go from asymmetrical to symmetrical. By symmetrical current we mean the envelopes of the peaks of the current waves that are symmetrical around the zero axis. If the envelopes are not symmetrical around the zero axis they are called asymmetrical current envelopes.

The envelope is a line drawn through the peaks of the wave as shown Figure 4. Most short circuit currents are nearly always asymmetrical during the first few cycles after the short circuit occurs. The short circuit current will have a maximum value during the whole cycle of the short circuit current that will be defined as i_p. It is most likely that this peak value will occur in the beginning, see Figure 4. The asymmetrical behavior of the current will pursue till breaking current defined as i_b see Figure 4. This sub-transient region is called the dynamical part of short circuit current. After the breaking current defined by i_b see Figure 4, the symmetrical short circuit current will pursue till transition to the thermal current. In this region, the behavior of the short circuit current can be characterized by root mean square (RMS value) that will be defined as initial symmetrical short circuit current denoted by $I_{k''}$ see Figure 4.

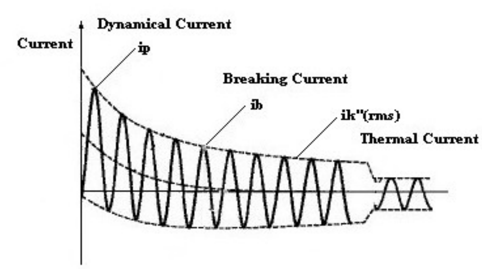


Fig. 4: Short circuit current oscillogram

DIgSILENT provides several different methods for short circuit analysis. Some methods like IEC 60909/VDE 0102 method, the ANSI method and the IEC 61363 method require less detailed network modeling i.e. require no load information [5]. The superposition method which is also known as complete short circuit method is used for the precise evaluation of the fault currents in a specific situation [5]. The complete short circuit method is selected in DIgSILENT to execute the short circuit analysis. The details about the nature of short circuit current and theory is presented in Appendix 1 of reference [3].

The parameters selected for complete short circuit method are defined in the table below:

Parameters	
Method	Complete
Fault Type	3-phase Short Circuit
Calculate	Max. Short Circuit Current
Break Time(s)	0.08
Fault Clearing Time(s)	1
Used Break Time	Global

TABLE II: Parameters for short circuit method from DIgSILENT

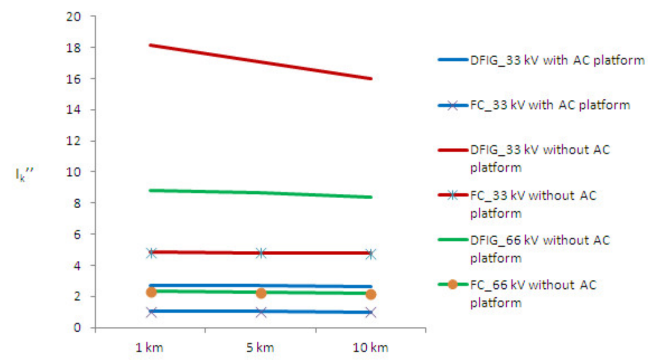
The short circuit contribution from HVDC (from grid side) is chosen as 150% of apparent power of the wind farms cluster initially and 50% thermally [3][6]

Two cases are investigated for short circuit analysis. In the first case, short circuit analysis of an offshore wind farm cluster connection to HVDC converter platform with and without using offshore AC collector platforms is simulated. In the second case, short circuit analysis at the feeders in the absence of offshore AC collector platform is simulated.

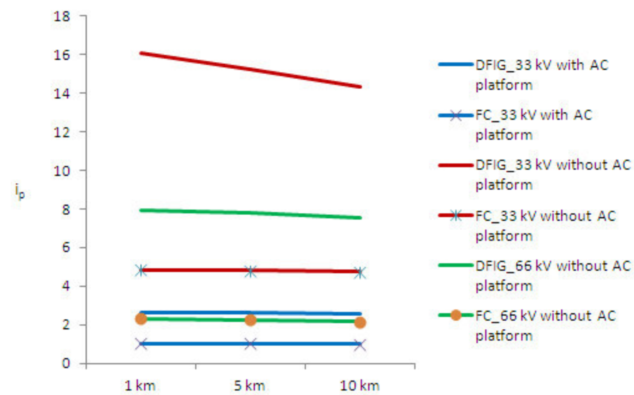
1) Short Circuit Analysis at HVDC Converter Platform Bus with and without AC Collector Platforms: In this case, the short circuit current behavior of the circuit from wind farms to the offshore HVDC converter platform bus is investigated. DFIG and FC generators are used in the simulations. The schematic circuit diagram is shown in Figure 2(a,b,c).

Distance between the wind farms and offshore HVDC converter platform is varied to estimate the short circuit currents at offshore HVDC converter platform bus. The length of export cable between wind farms and HVDC converter platform is varied from 1 km to 10 km.

The internal voltage of the wind farm is chosen as 33 kV for the topology with and without AC platform comparison cases. 33 kV and 66 kV are also compared in the absence of the offshore AC collector platforms.



(a)



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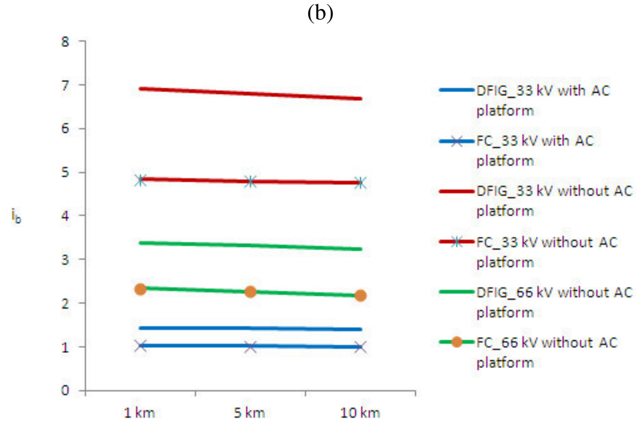

(c)

Fig. 5: Short circuit currents(normalized)in kA at HVDC converter platform bus for different connection options and different types of wind turbine generators (a) $I_{k''}$ (b) i_p and (c) i_b for a 804 MW Wind Farm

In Figure 5, the initial symmetrical short circuit current ($I_{k''}$), peak short circuit current (i_p), and peak short circuit breaking current (i_b) are presented for offshore HVDC converter platform bus. Different connection options are compared for two different types of wind turbine generators i.e. DFIG and FC generators.

It has been evident from the Figure 5 that the short circuit current levels will increase after the removal of AC collector platforms from the offshore wind park connection to offshore HVDC converter platform.

For DFIG and FC generators, it is observed that the short circuit currents, ($I_{k''}$, i_p, and i_b) for 33 kV internal grid without AC collector platform, increased approximately by 4 to 6 times than those with AC collector platform as shown in Figure 5.

For doubly fed induction generators and full conversion generators, it is observed that the short circuit currents, ($I_{k''}$, i_p, and i_b) for 66 kV internal grid without AC collector platform, increased approximately by 2.5 to 3.5 times than those with AC collector platform Figure 5.

It is estimated that the short circuit current levels of doubly fed induction generators are approximately 2.5 to 3.5 times higher than those of full conversion generators. The full conversion generators show quite stable short circuit current levels with the increase in distance between wind farms and HVDC platform while short circuit currents decrease for DFIG with the increase in distance between wind farms and HVDC platform.

2) Short Circuit Analysis at the Feeders in the Absence of AC Collector Platform: Short circuit can occur in any of the individual feeder of the wind farm just behind the circuit breaker, the current from all other feeders and also from the main transformer or HVDC system can pass through the fault point via bus bar. In Figure 8, such scenario is shown:

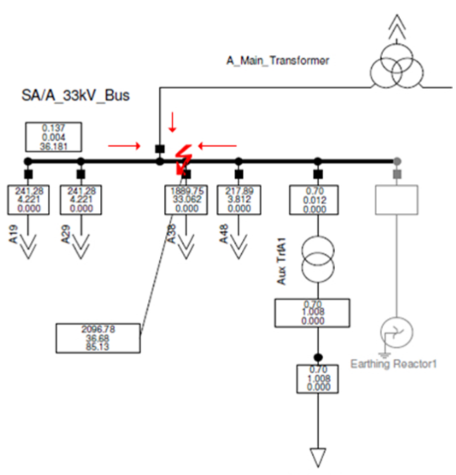

Fig. 6: Peak short circuit breaking current (normalized) (i_b)in kA at individual feeders for two different types of wind turbine generators in the absence of AC collector platform

The peak short circuit breaking current is important when the fault is near the generator and protection is ensured by time delayed circuit breakers so it is quite important to estimate the peak short circuit breaking current (i_b) in such scenario.

In the absence of offshore AC collector platforms, three different length of cables between the last wind turbine in the feeder and offshore HVDC converter platform are selected. Two wind turbine generator types are compared for 33 kV and 66 kV. The results are shown in Figure 9.

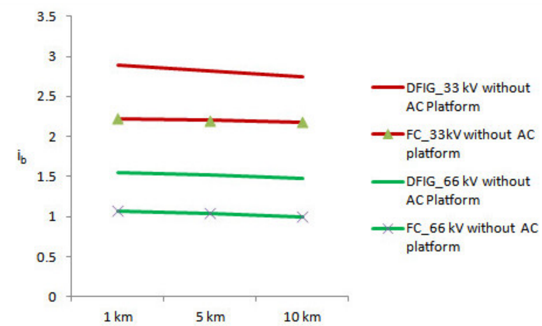

Fig. 7: Peak short circuit breaking current (normalized) (i_b)in kA at individual feeders for two different types of wind turbine generators in the absence of AC collector platform

It can be observed from the Figure 7 that the peak short circuit breaking current (i_b) has higher values for 33 kV without AC platform compared to 66 kV without AC platform.

IV. Conclusion

The main purpose of this study is to compare the two topologies of an offshore wind farm cluster connection to the offshore HVDC converter platform. It was observed that 33 kV with AC and 33 kV without offshore AC collector platform configurations shows that the effects of removing the offshore AC collector platform will be significant on losses for distances less than 10 km. This will improve the losses for less than 10 km for 33 kV without offshore AC platform case. At 10 km this trend is reversed.

It was also observed that the annual energy losses of the topology using 33 kV internal wind farm voltages without offshore AC collector platform are higher than those observed by using 66 kV internal wind farm voltages without offshore AC collector platform.

It is estimated that the short circuit current levels of DFIG are approximately 2.5 to 3.5 times higher than those of FC generators. The full conversion generators show quite stable short circuit current levels with the increase in distance between the offshore wind farms and offshore HVDC platform while short circuit currents decrease for DFIG with the increase in distance between wind farms and offshore HVDC converter platform. Short circuit analysis at the feeders in the absence of AC collector platform was also investigated.

The higher levels of short circuit currents at HVDC converter platform, in the absence of an offshore AC collector platform, can be controlled by different short circuit protection strategies i.e. current limiting fuses, circuit breakers, series coils and using three winding transformers at HVDC converter platform.

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