

D1.2 – Definition of the use-cases and their applications



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PROJECT SUMMARY

SiC4GRID is a 42-month project gathering partners from the complete value chain of SiC-based converters collaborating to tackle current obstacles to the technologies' market uptake. SiC4GRID thus aims for an optimised integrated SiC-based technology composed of three-fold innovations in terms of hardware, software and IoT.

To optimise both techno-economic and environmental pillars, the consortium will design, produce, test and validate an integrated product composed of a 30% smaller size energy-efficient SiC-based power module competitive with state-of-the-art technology and coupled with an adapted optimised self-healing energy management system (EMS). This EMS amplifies the benefits of a strong system-level IoT architecture and adapted digital tools such as digital twin and optimisation algorithms.

Throughout the project, the circularity and eco-design of all steps of the converter manufacturing process will be targeted with a strong emphasis on resource optimisation and carbon emission reduction. The testing phase will be done both as an integrated modular converter on a physical test bench, as well as digitally to increase the variety of relevant applications and real-condition scenario. For the digital simulations, three use-cases will therefore be chosen to increase the validated parameters and scope of applications, including MMC and SST converters, onshore/offshore wind and PV applications, as well as the potential for storage.

Overall, the project contributes to advancing the market readiness of the technology by lowering its cost (30% cost reduction compared to silicon converters), its size (15% size reduction), its lifetime (30+ years) and its environmental impact (30% resource consumption reduction and 50% CO2 emission reduction). In the longer-term, SiC4GRID will thus also help renewable energies integrate the energy grid and bring European leadership to the forefront of converter technology providers.

OBJECTIVE AND EXECUTIVE SUMMARY

The overall objective of this deliverable is to define realistic use-case scenarios relevant to the use of silicon carbide-based converters. These use-cases will then be used as a common baseline to lead the innovations and optimizations. Based on this common ground the demonstration plan scenario will be defined and a SiC-based module will be proposed in WP5 of SiC4GRID project.

The main goal of this deliverable is to define the use-case scenarios most suitable to meet the SiC4GRID general objectives, starting from the scenarios identified at the proposal stage. These use-cases cover a set of configurations in terms of type, size and topology of renewable farms (PV and wind) and the main characteristics of the grid at the point of connection. The use-cases focus on applications based on alternative MVDC topologies, with innovative SiC-based modules and converters. The use-case applications will guide the development of converters based on the same technological brick to assess its adaptability, scalability, applicability and operation performance in different realistic operating scenarios through the definition of functional specifications.

The deliverable details:

- (1) One MVDC PV farm use-case based on an MVAC PV farm reference. This use-case assumes the use of a solid-state transformer as a mean of transforming the PV string voltage (1.5 kV) to inter-array voltage (± 40 to ± 60 kV). The installed power of the farm is 250 MW and easily adaptable to higher powers. A 10 MW building block of this use-case is shown in the figure below.

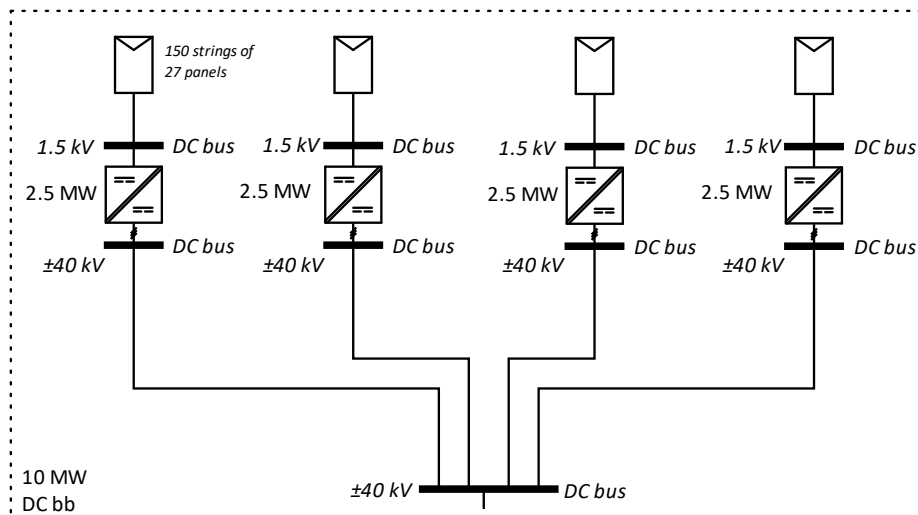


Figure 1 – MVDC PV farm use-case: 10 MW building block

- (2) Two MVDC wind farm use-cases:
 - a. MVDC wind farm use-case with a DC turbine of 20MW using modular multilevel converter (MMC). Here, the MMC is used as an AC/AC converter, adapting the generator voltage to the diode rectifier unit (DRU). The DRU then rectifies the voltage to adapt it to MVDC side. The figure is illustrated below.

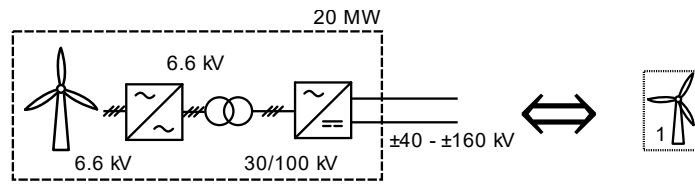


Figure 2 - First DC wind turbine use-case

- b. MVDC wind farm use-case with a DC turbine of 20 MW using solid-state transformer (SST). Here, a rectifier converts the generator voltage to DC voltage, later adapted to the MVDC side using the SST. This use-case is illustrated below.

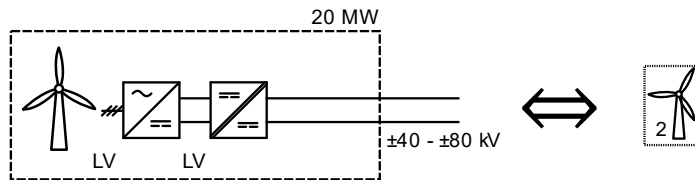


Figure 3 – Second DC wind turbine use-case

The use-cases reflect the way the MVDC offshore wind farms can be implemented. Several inter-array topologies and export structures are proposed for different installed power levels of wind farms (small/medium, large and very large). This illustrates different ways the DC wind turbines can be used in the SiC4GRID project.

Converter requirements, both MMC and SST, based on SiC are detailed as well. The advantages of using SiC over Si and the ways this can be implemented in the specific use-case are addressed too.

In conclusion, the use-case scenarios were constructed based on a thorough review of relevant literature and project analysis, starting with a reference HVAC/MVAC use-case, and leading to the construction of HVDC/MVDC use-cases for both PV and wind farms. These scenarios provide a common baseline for the development of innovative and optimized solutions for the project and serve as a guide for the development of converters based on the same technological brick.

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ABBREVIATIONS AND ACRONYMS

Table 1 - List of acronyms

Acronym	Description
BO	Back Office
CA	Consortium Agreement
CINEA	European Climate, Infrastructure and Environment Executive Agency
CM	Consortium Meeting
DoA	Description of Action
EB	Executive Board
EC	European Commission
EU	European Union
GA	General Assembly
PM	Person-Month
TL	Task Leader
WBS	Work Breakdown Structure
WP	Work Package
WPL	Work Package Leader
MMC	Modular Multilevel Converter
MPPT	Maximum Power Point Tracking
SST	Solid-State Transformer
PV	Photo voltaic
MVDC	Medium Voltage Direct Current
HVDC	High Voltage Direct Current
DC	Direct Current
DRU	Diode Rectifier Unit
MVAC	Medium Voltage Alternating Current
AC	Alternating Current
MV	Medium Voltage
HV	High Voltage
LV	Low Voltage
DAB	Dual Active Bridge
NPC	Neutral Point Clamped
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
VSC	Voltage Source Converter
MF	Medium Frequency
HF	High Frequency
IGBT	Insulated Gate Bipolar Transistor
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
XLPE	Cross-Linked Polyethylene
HVAC	High Voltage Alternating Current
LCOE	Levelised Cost Of Energy
SG	Synchronous Generator
PMSG	Permanent Magnet Synchronous Generator
MFT	Medium Frequency Transformer
WT	Wind Turbine

TBD	To Be Determined
WTG	Wind Turbine Generator
RH	Relative Humidity

Table 2 - Partners Acronyms

No.	Participant name	Acronym	Country
1	VRIJE UNIVERSITEIT BRUSSEL	VUB	BE
2	AALBORG UNIVERSITET	AAU	DK
3	ELECTRICITE DE FRANCE	EDF	FR
4	SOITEC AS	SOITEC	FR
5	POWERCON AS	PWC	DK
6	KK WIND SOLUTIONS AS	KKW	DK
7	INFORMATION TECHNOLOGY FOR MARKET LEADERSHIP	ITML	EL
8	MONDRAGON GOI ESKOLA POLITEKNIKOA JOSE MARIA ARIZMENDIARRIETA S COOP	MGEP	ES
9	EUROQUALITY SARL	EQY	FR
10	HITACHI ABB POWER GRIDS LTD.	HE	CH
11	CSEM CENTRE SUISSE D'ELECTRONIQUE ET DE MICROTECHNIQUE SA - RECHERCHE ET DEVELOPPEMENT	CSEM	CH
12	AMANTYS POWER ELECTRONICS LTD	AMTS	UK

1 GENERAL DELIVERABLE INTRODUCTION

The overall objective of this deliverable is to define realistic use-case scenarios relevant to the use of silicon carbide-based converters. These use-cases will then be used as a common baseline to lead the innovations and optimizations. Based on this common ground the demonstration plan scenario will be defined and a SiC-based module will be proposed in WP5 of SiC4GRID project.

The main goal of this deliverable is to define the use-case scenarios most suitable to meet the SiC4GRID general objectives, starting from the scenarios identified at the proposal stage. These use-cases cover a set of configurations in terms of type, size and topology of renewable farms (PV and wind) and the main characteristics of the grid at the point of connection. The use-cases focus on applications based on alternative MVDC topologies, with innovative SiC-based modules and converters. The use-case applications will guide the development of converters based on the same technological brick to assess its adaptability, scalability, applicability and operation performance in different realistic operating scenarios through the definition of functional specifications.

The use-cases in this deliverable are thus constructed in the following manner:

- Bibliography and project review on the current installations.
- A reference MVAC use-case is proposed. These use-cases, both PV and wind, are representative of the today's projects in operation. They are used as a starting point in construction of the MVDC use-cases for the SiC4GRID project.
- An MVDC use-case is then constructed and presented.

The deliverable outline is as follows:

- Chapter 2 presents the bibliography review on PV MVAC farms, their topologies and building blocks. It presents the reference PV MVAC farm use-case.
- Chapter 3 deals with alternative MVDC topologies and the concept analysis.
- Chapter 4 presents the MVDC PV farm use-case, the first use-case for the SiC4GRID project. It outlines the topology and the PV farm ratings. Further, it specifies the converter level requirements and the requirements relative to SiC.
- Chapter 5 presents the bibliography review on wind MVAC farms, their topologies and building blocks. It presents the reference MVAC wind use-cases.
- Chapter 6 discusses the alternative MVDC and HVDC concepts for MVDC wind farms. It presents the bibliography review and different hypotheses taken for the MVDC use-case construction.
- Chapter 7 presents the two MVDC wind use-cases, the second and the third use-case for the SiC4GRID project. It outlines the topology of the wind turbine and its ratings. Further, it specifies the converter level requirements and the requirements relative to SiC.

2 PV FARM – REFERENCE USE-CASES

PV is one of the most popular energy sources nowadays. PV uses semiconductor technologies to convert the energy from sunlight to electricity and therefore operates when there is enough energy from the sun during a day. Due to the intermittence of the solar energy, it needs to be mixed with other sources of energy, or an energy storage solution. The PV market is very promising, and it plays a key role on the energy map of various European countries.

The PV systems can be broadly classified into different categories according to the installed power. Here, we consider very large scale (higher than 100 MW) PV systems. The following paragraphs will deal with MVAC PV farm topologies in this category and their MVDC counterparts. Firstly, different PV MVAC topologies are reviewed, both for inter-array grid system and power conversion systems. Then, MVDC alternative concepts are proposed, permitting the evaluation of the innovative SiC-based modules and converters.

2.1 REFERENCE PV FARM TOPOLOGIES

A key component of a PV farm is its inter-array topology, which refers to the arrangement of PV modules and their interconnections within the farm. The choice of inter-array topology can have significant impacts on the overall performance, efficiency, and reliability of the PV farm. In this section, we will explore various inter-array topologies commonly used in large-scale MVAC PV farms and their advantages and disadvantages.

2.1.1 Radial topology

The radial configuration has several numbers of PV panels connected to one feeder (MV cable), as shown in Figure 4. When compared to others, this topology is the simplest and the cheapest which makes it interesting. However, its low reliability is a big disadvantage. In fact, one can note that if the first feeder is lost, all strings are lost as well.

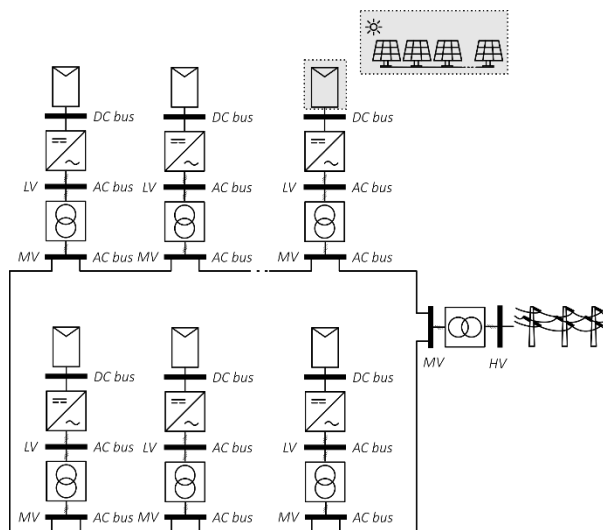


Figure 4 -Radial PV farm

2.1.2 Ring topology

The reliability issue of the radial configuration can be mitigated using a ring PV plant topology. In this case, the connection is based on an additional feeder in the other side of the string, as shown in Figure 5. If one of the inverters in the figure fails, the other ones can continue to operate. This reduces downtime and increases the reliability of the PV farm. The drawback here, however, is the complexity and the cost of the installation (the cable cross section must be the same for the whole loop, which is not the case for the radial configuration).

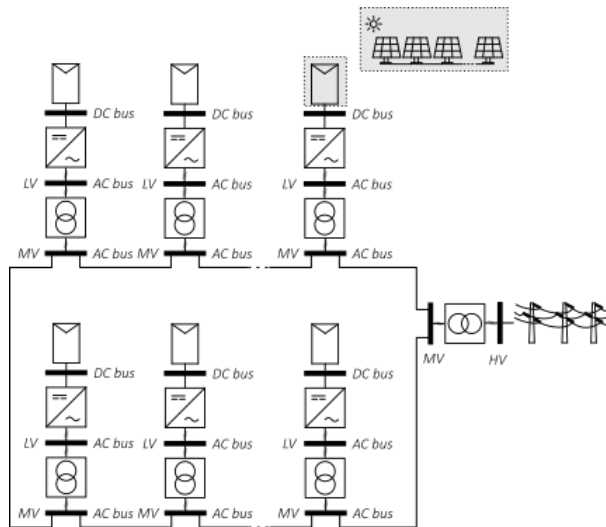


Figure 5 -Ring PV farm

2.1.3 Star topology

In the star PV topology, each of the PV arrays is directly connected to the main collector. Usually, in order to reduce the cable losses, this collector is ideally in the middle of the PV farm. This solution offers high reliability but increases the cost of cables (the same cross section as for inter-array cables can be used, however).

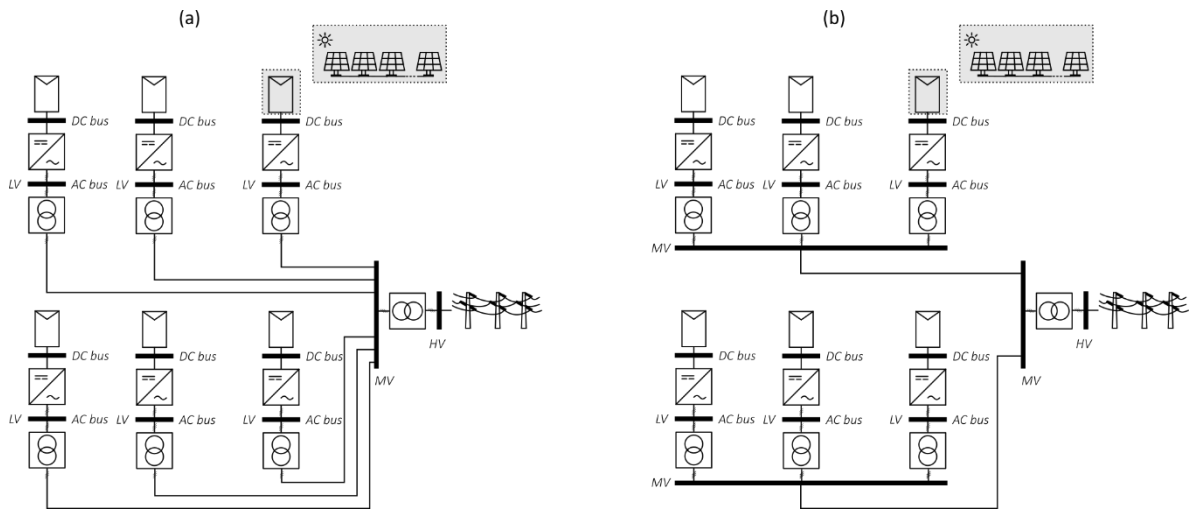


Figure 6 – Star PV farms

2.1.4 Reference MVAC PV farm

In this paragraph, the reference MVAC PV farm use-case is presented. This will be used as a starting point allowing the construction of the MVDC PV farm use-case in the SiC4GRID project.

The proposed reference MVAC case is a PV farm shown in Figure 7, reflecting the current PV farms. It consists of:

- 10 MW building block, described in the next section (2.2).
- Several of these building blocks are connected in series forming an array (two in the example below)
- Several of these arrays are connected to the same DC bus collector at MVDC level (three in the example below to form 60 MW feeder block).
- This is then multiplied several times to form a PV farm of several hundred MW in total (typically, we can use 240 MW as our use-case below, which power corresponds quite well to the standard power transformer ratings of 250/270 MVA needed at the point of common coupling).

This configuration of a PV MVAC farm can then be multiplied in order to reach higher power levels (ex: multiply the configuration four times to reach 1 GW of installed power).

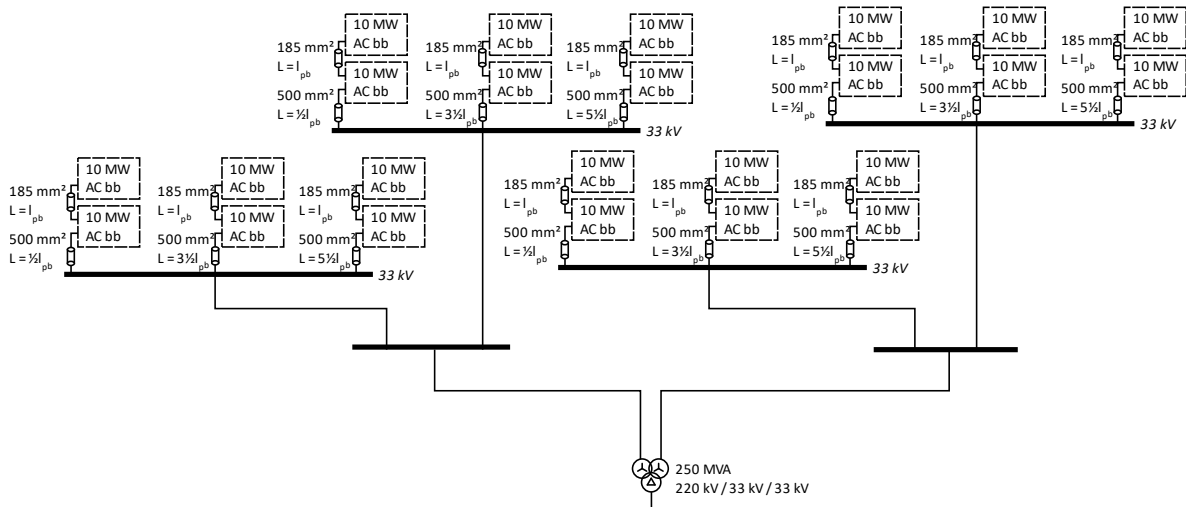


Figure 7 – Reference PV MVAC topology 250MW

2.2 REFERENCE PV FARMS POWER CONVERSION STATIONS

Different power conversion station topologies can be considered for the above-mentioned PV farms. They are in detailed in the next subsection and a reference topology is then selected.

2.2.1. Power conversion station topologies

The interconnection between PV panels and the corresponding inverters is illustrated in Figure 8:

- The central topology assumes a connection of several hundreds of PV panels to one inverter
- In the string topology, the PV arrays are connected to one string inverter
- In the multi-string topology, the PV string is connected to a DC/DC converter and afterwards a couple of these DC/DC converters are connected to a single inverter
- The module integrated topology has one inverter per panel (otherwise known as micro inverter).

The inverter topology is commonly selected based on the electrical characteristics of the system, according to the details in Table 3.

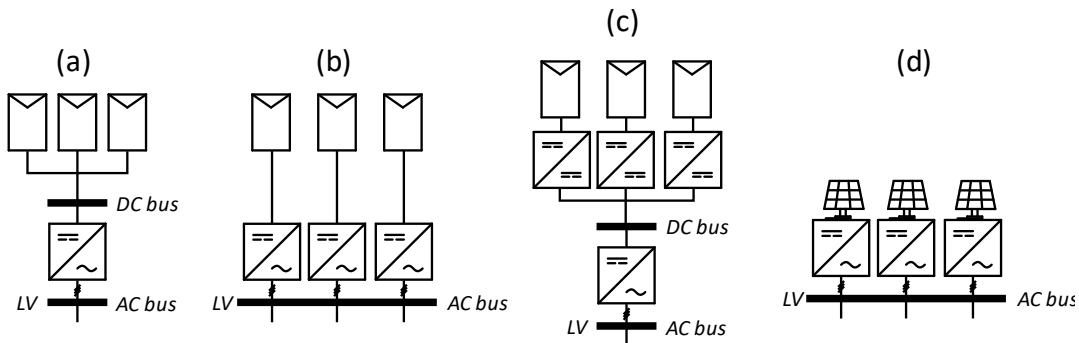


Figure 8 -PV inverter topologies (a) central, (b) string, (c) multistring, (d) module integrated (micro-inverter)

Table 3 –Electrical characteristics of PV inverter topologies [1]

Inverter topology.	P (kW)	V _{in} MPPT DC (V)	V _{out} AC (V)	f (Hz)
Central	100-2500	400 – 1500	270 – 400	50, 60
String	0.4 – 5	200 – 500	110 – 230	50, 60
Multi-string	2 – 30	200 – 800	270 – 400	50, 60
Module integrated (micro-inverter)	0.06 – 0.4	20 – 100	110 - 230	50, 60

These topologies can generally be compared using four criteria, as detailed in Table 4:

- **general characteristics**, such as reliability, MPPT efficiency, flexibility etc,
- **power losses** considering switching, AC and DC losses,
- **power quality**, influenced by the DC and AC voltage variations and voltage balance, and
- **cost**, involving installation, maintenance, land cost and length of cables in the DC and the AC side.

Table 4 – Comparison of PV inverter topologies [1]

		Central	String	Multi-string	Module integrated
General	Reliability	Low	High	Medium	Very high
	Robustness	High	Low	Medium	Very low
	Flexibility	Low	High	Medium	Very high
	MPPT efficiency	Low	High	Medium	Very high
Power losses	Mismatching	High	Low	Low	Very low
	Switching	High	Low	Medium	Very low
	AC power losses	Low	Medium	Medium	High
	DC power losses	High	Low	Medium	Very low
Power quality	AC voltage variation	Low	High	Medium	Very high
	DC voltage variation	Very high	Medium	High	Very low
	Voltage balance	High	Medium	Low	Low
Cost	Installation cost	Medium	High	Medium	Very high
	DC cables	High	Low	Medium	Very low
	AC cables	High	Medium	Medium	High
	Maintenance	Low	Medium	High	Very high
<i>Advantages</i>		<i>Low power electronics cost optimum, easy maintenance</i>	<i>Good MPPT performance</i>	<i>Individual string control</i>	<i>Optimal panel tracking</i>
<i>Disadvantages</i>		<i>Inverter sensitivity to the DC voltage</i>	<i>Inverter sensitivity</i>	<i>Complexity</i>	<i>Maintenance</i>

In the case where the PV inverter has a power rating higher than 500 kW, it is common to use a three-winding transformer (one MV and two LV windings) [1]. For PV inverters with a power rating lower than 500 kW, two-winding transformers are commonly used. The connection of medium voltage transformers is illustrated in Figure 9.

The transformer is chosen according to the power rating, efficiency, cost and size [2]. However, as the transformers used nowadays are of 50/60 Hz, researchers are looking for another type of transformers to reduce the footprint (both in surface, volume, and resources) occupied and to improve the reliability of the PV farms. A medium-frequency transformer seems to be a good solution for this, but it would need additional conversion stages to reach medium level frequencies.

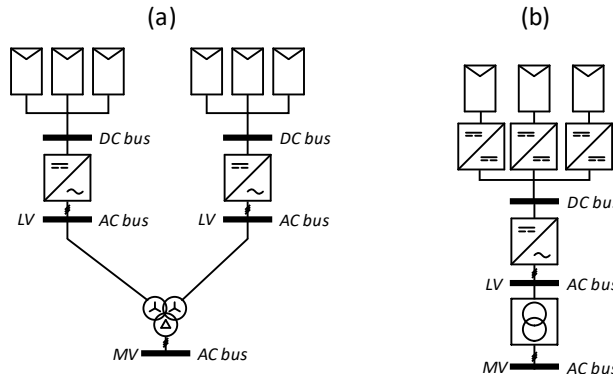


Figure 9 – Connection of medium voltage transformers: (a) Central PV inverter with a three-winding transformer, (b) Multistring PV inverter with a two-winding transformer

2.2.2. Reference power conversion station

When it comes to the power converter station:

- 27 panels¹, each of 615 W form a string²
- 150 such strings are connected to the 2.5 MW DC/AC converter on the LV side
- The DC/AC converter provides the AC voltage and is connected to one of the two low voltage sides of a three-winding transformer.
- The other low voltage side of the transformer is connected to an identical configuration
- The medium voltage side of the transformer is connected to a MVAC bus.

Several parameters must be taken in account to define the length of the cable between the 10MW DC building blocks, shown in the Figure 10:

- the panel size $1.12 \times 2.5 \text{ m} = l_{\text{panel}} * L_{\text{panel}}$
- the covering ratio, C_{cov} , typically 30% to 70%
- the space used to service the panels (road, power stations)
- The angles of the panels, α_p , with the ground typical. latitude – 10°

Thus, the area covered by the panels in the 10MW block is defined by

$$\text{Area}_{10\text{MW}b\text{loc}} = l_{\text{panel}} * L_{\text{panel}} * \cos(\alpha_p) * 600 * 27 * C_{\text{cov}}^{-1}$$

If we use square bloc and we neglect the space used by the service road and the power substations. The length of the square 10 MW bloc is given by l_{pb} :

$$l_{pb} = \sqrt{l_{\text{panel}} * L_{\text{panel}} * \cos(\alpha_p) * 600 * 27 * C_{\text{cov}}^{-1}}$$

This configuration forms a building block of 10 MW, with an MVAC output, here named *10MW AC bb*. The ratings are summarised in Table 5.

¹ A standard solar panel is assumed: 1.1 x 2.5 m and 615 W.

² Limited by voltage of 1.5 kV today

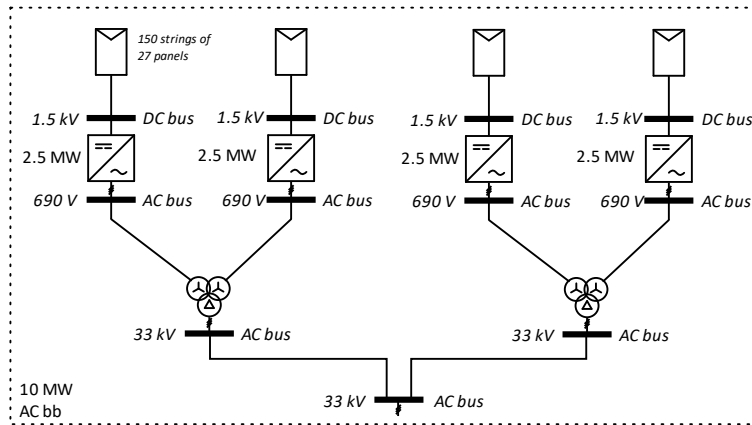


Figure 10 – Reference AC building block

Table 5 – Ratings of the AC building block

Rating		Unit
PV panel		
Power	615	W
Size	1.1 x 2.5	m
Covering coefficient	40	%
Angle α_p	Latitude -10	°
N° panels per string	27	
N° strings	150	
DC/AC converter		
DC side voltage	1.5	kV
AC side voltage	690	V
Power	2.5	MW
Transformer		
High voltage side	33	kV
Low voltage side	690	V
Power	5	MW

The cables used for the inter-array system must comply with current and rated voltage levels. Table 6 shows the current ratings for available three-core cross-linked polyethylene (XLPE) AC land cables. These are average values that can differ from actual value depending on the laying configuration (soil condition, flat or trefoil, screen earthing, etc...)

The cross-section typically used are in the range of 185, 300, 500 mm² aluminium for 33 kV AC inter-array grid system.

Table 6 – Current rating for three-core land cables [3]

Cross-section (mm²)	Copper conductor (A)	Aluminium conductor (A)
95	330	260
120	370	295
150	410	325
185	455	365
240	515	420
300	570	465
400	630	520
500	695	585
630	760	650
800	820	710
1000	870	775

3 PV FARM - ALTERNATIVE MVDC CONCEPT ANALYSIS

The power energy systems evolve with the fast development of the power electronic converter-based DC technology. This technology raises more and more attention in many applications, and especially in renewable energy systems.

The feasibility, operation, control and protection of DC networks has been studied for some years. Moreover, the feasibility of converting existing AC distribution grids into DC has been studied as well [3] [4] [5].

To provide high-efficiency conversion and a lightweight system, MVDC collection (with HVDC transmission for example) can be used to interface numerous DC sources to the grid. A good option is to use a high step-up ration DC/DC converter to transfer the generated electrical power from the lower output voltage of PV modules. These converters should be able to deal with high voltage and high power and provide high step-up ratio, electrical isolation, and high efficiency. They should implement MPPT as well. Several solutions have been proposed for this DC/DC converter: Multilevel DAB, 3L NPC based DAB, 3-phase DAB, converters with ZVS or ZCS, resonant converters etc.

3.1 ALTERNATIVE MVDC TOPOLOGIES

The MVDC PV farm topologies do not differ a lot from the MVAC topologies. In fact, with MVDC, it is common to use the same three types of topologies: radial (Figure 11), ring (Figure 12) and star (Figure 13).

The main difference here is the use of DC cables instead of AC and the use of a DC collector instead of AC collector. The advantage of the DC cables over AC is the suppression of reactive losses and thus the increased capacity of transfer. Moreover, MVDC technology needs less cables than MVAC.

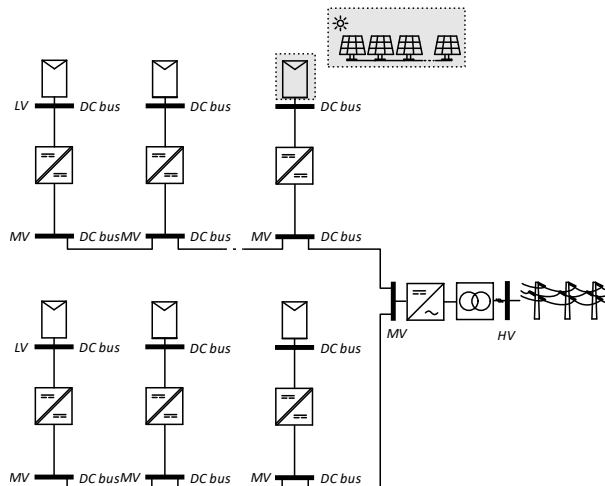


Figure 11 – Radial MVDC PV farm topology

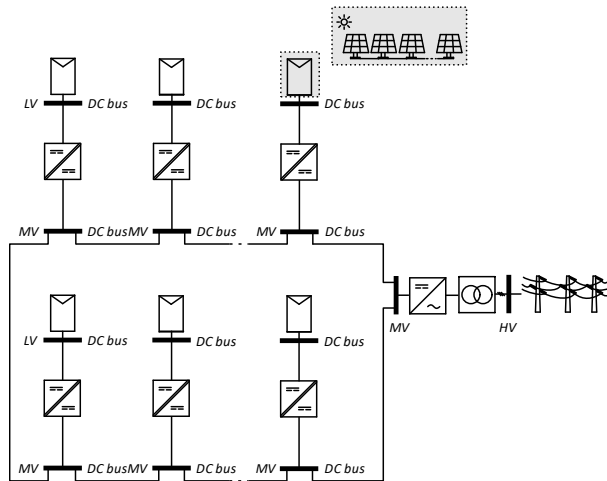


Figure 12 – Ring MVDC PV farm topology

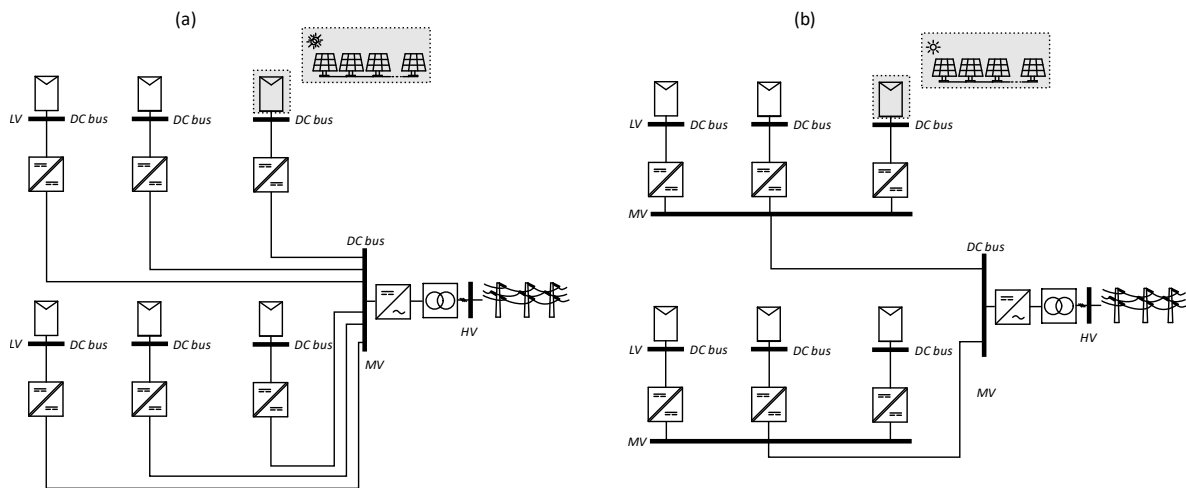


Figure 13 – Star MVDC PV farm topology

When discussing the MVDC alternative topologies for the inter-array cable systems, it is worth to look at the “equivalent” power, voltage and cross-section of the MVDC alternative inter-array grid system. Let us consider a DC cable whose two cross-sections (two cores per bi-pole) are in the same range as the AC “equivalent” cable three cross-sections (three cores per cable). This allows to consider the same amount of aluminium (or copper) in the DC cable as in the AC cable.

The power and ampacity capabilities of the cable given bellow do not consider extensive optimisation or accurate sizing regarding the laying and environmental conditions. Instead, a representative hypothesis is considered to achieve a fair benchmark between AC and DC inter-array grid systems.

Typically, the ratings are considered with a close laying bundle configuration: bi-pole land cable – aluminium conductor – Cable with a burial depth around 1 m (soil temperature of 15°C, soil thermal resistivity 1.0 K.m/W) as usually given in supplier datasheets.

Table 7 – Power transmission capacity for DC bi-pole cables

	Cross-section Aluminium	MVDC (+/- kV DC)			
		20	30	40	60
Transmitted power per bi-pole (MW)	bi-pole 2x300 mm ²	20	29	39	59
	Bi-pole 2x500 mm ²	26	40	53	79
	bi-pole 2x630 mm ²	29	43	58	86
	bi-pole 2x800 mm ²	35	52	70	104

Table 8 – Land cable ampacity capabilities for considered cross-sections

Cross-section (mm ²)	Land DC cable	
	Aluminium conductor (A)	Copper conductor (A)
95	250	340
150	330	440
240	430	580
300	490	660
500	660	880
630	720	1000
800	870	1170
1000	1000	1250

3.2 ALTERNATIVE MVDC POWER CONVERSION STATION

The alternative MVDC power conversion station is inspired by the MVAC one. The idea is to replace the inverter with a DC/DC converter that allows to reach MVDC levels.

The PV array is thus connected to a DC/DC converter that must play several roles: voltage step-up, galvanic isolation and MPPT. This allows to replace the inverter and its transformer with a conversion block that keeps the same functions.

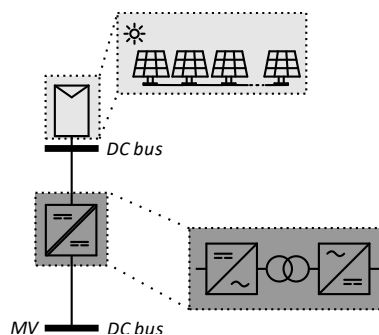


Figure 14 - Basic power conversion station

When it comes to rating, it is expected for the DC/DC converter to be able to operate at 1.5 kV at the low voltage side and up to $\pm 20 - \pm 60$ kV on the medium voltage side.

Table 9 summarises the requirements of DC/DC converters for MVDC PV farms.

Table 9 – Requirements of DC/DC converters for MVDC PV farms

PV farms	
Step ratio	High
Power	High
Galvanic isolation	Required
Bidirectionality	Unnecessary
VSC scheme	Unipolar – Bipolar
Fault blocking / ride through capability	Required

4 PV FARM - ALTERNATIVE MVDC USE-CASE DEFINITION (SPECIFICATION, REQUIREMENTS)

This chapter will summarise the proposed MVDC PV farm use-case for the SiC4GRID project.

4.1 PV FARM USE-CASE

The proposed use-case is an MVDC PV farm, as shown in Figure 15. It consists of:

- 10 MW building blocks, described in the next paragraph, and shown in Figure 16.
- Several of these building blocks are connected in series forming an array (two in the example below)
- Several of these arrays are connected to the same DC bus collector at MVDC level (three in the example below to form 60 MW feeder block).
- This is then multiplied several times to form a PV farm of several hundred MW in total (Typically, we can use 240 MW as our use-case bellow, which power corresponds quite well to the standard power transformer ratings of 250/270 MVA needed at the point of common coupling).
- A battery is added to the MV bus, via an DC/DC converter

This configuration of a PV MVDC farm can then be multiplied to reach higher power levels (ex: multiply the configuration four times to reach 1 GW of installed power). The calculation of l_{pb} is given in §2.1.4.

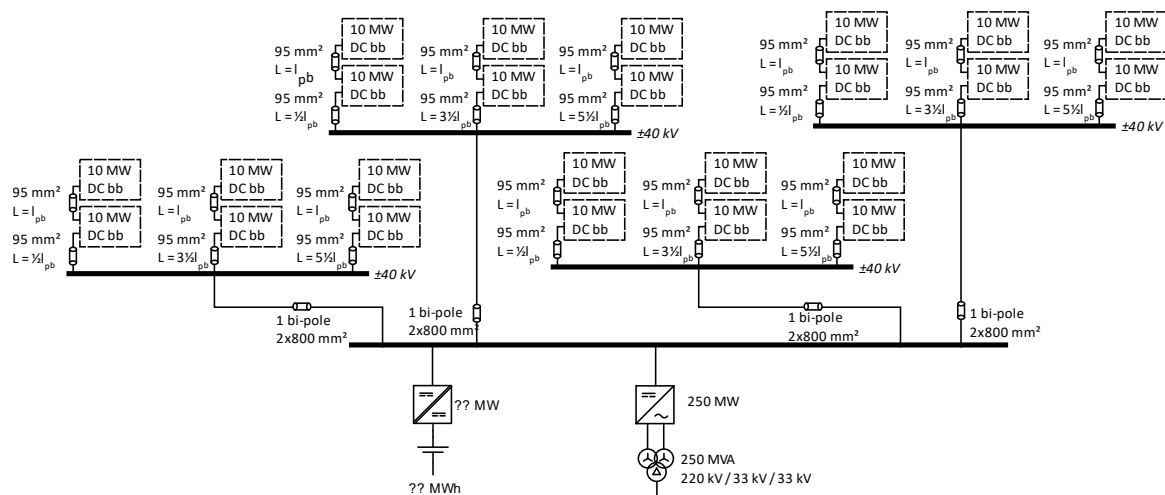


Figure 15 – MVDC 240 MW PV farm use-case

Remark: the use-case presented is given as examples to illustrate the problematic. The inter-array rated voltage (± 40 kV to ± 60 kV), number of building blocks and specific configuration shall be determined according to the optimisation in WP2, considering the global trade-off relative to rated powers, rated voltages and cable cross-sections, among other constraints.

The battery sizing will also be a part of the WP2 and will be determined through optimisation.

4.2 POWER CONVERTER STATION (MVDC – 10 MW SIC BASED SST)

When it comes to the power converter station:

- 27 panels³, each of 615 W form a string
- 150 such strings are connected to the 2.5 MW DC/DC converter on the LV side
- The DC/DC converter steps up the voltage to the MV level

This configuration forms a building block of 10 MW, with an MVDC output, shown in Figure 16 and named *10MW DC bb*. The ratings are summarised in the table below.

Table 10 – MVDC building block ratings

	Rating	Unit
PV panel		
Power	615	W
Size	1.1 x 2.5	m
Covering coefficient	40	%
Angle α_p	Latitude – 10	°
N° panels per string	27	
N° strings	150	
DC/DC converter		
LV	1.5	kV
MV	$\pm 20 - 60$	kV
Power	2.5	MW

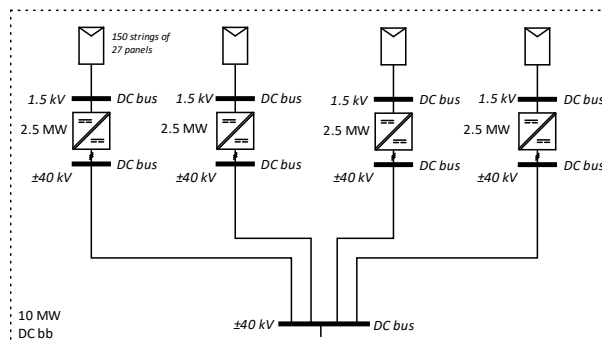


Figure 16 – MVDC 10 MW building block

The specific converter level requirements are detailed in the next subsections.

4.2.1 Converter level requirements

As shown in Figure 17, the considered PV converter block is an SST converter. The main building block of the SST converter is an isolated DC-DC converter. The galvanic isolation in solid-state transformer is realized by medium frequency (from few kHz to few 10 kHz) transformers. With increased switching frequency the power density of these transformers can be improved. The multiple number of these converters (cell), in various serial and/or parallel connections, give flexibility to adjust the delivered power and output voltage of the system.

³ A standard solar panel is assumed: 1.1 x 2.5 m with 615 W.

Some calculations for the SST-based converter

We consider a standard PV DC link voltage around 1500V. In this case the converter input current at 2.5 MW will be:

$$V_{dc_in} = 1500 \text{ V}$$

$$P = 2.5 \text{ MW}$$

$$I_{dc_in} = \frac{P}{V_{dc_in}} = 1666 \text{ A}$$

The presented power module's voltage and current rating can fulfill this voltage range and with paralleled input also the current criteria.

Looking at the output stage of the DC-DC converter using SiC power modules with same ratings and:

- $V_{dc_out} = \pm 20 \text{ to } \pm 60 \text{ kV}$
- *Allowed $V_{dc_out/module(cell)} = 2000\text{V}$ (maximum allowed due to the voltage rating of the half-bridge modules)*

The system will require an increased number of individual cells so that require space will also increase due to MV isolation criteria.

Considering PV characteristics, unidirectional power flow is expected, so passive switching components can also be used for rectification. Considering this, replacing the MV side switching MOSFETs of each cell with higher voltage rated SiC diodes (5+ kV) can be a good solution. So, the required output MVDC voltages can be easier reached with a reduced number of modules (cells) connected in series. In this case special attention should be made to the MF/HF transformer isolation requirements.

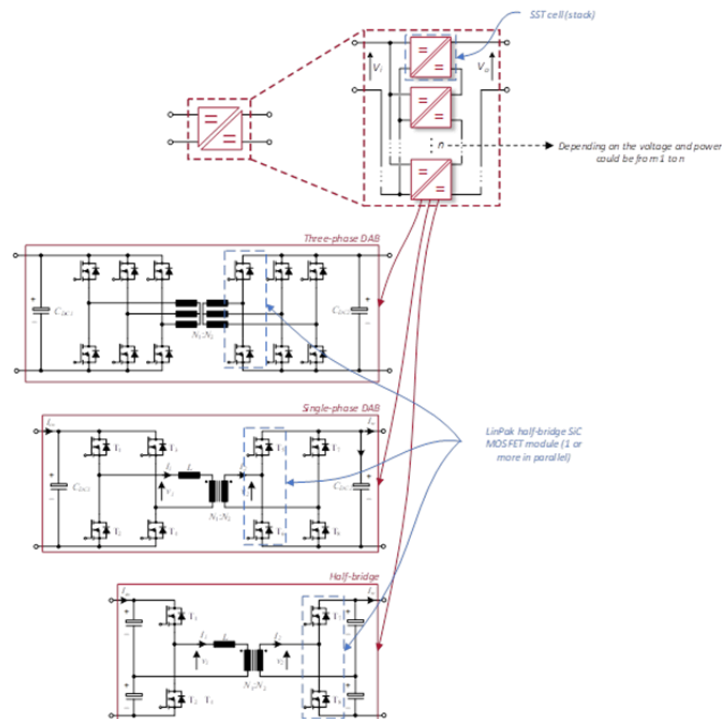


Figure 17 – 2.5 MW DC-DC converter structure

4.2.2 Characteristics of the SiC based converter

Lower switching losses

In comparison to Si IGBTs, that are used for high current applications with higher blocking voltages though operated at low to medium switching frequencies, higher switching frequency can be applied to SiC MOSFETs with similar voltage and current characteristics due to *lower switching losses*.

Better thermal management

Excellent *thermal conductivity* of the SiC MOSFETs allows better thermal management. SiC chips can handle much higher currents, compared to same sized Si MOSFET chips. The operating junction temperature is also higher, up to 175°C.

Improved power density

The switching performance of SiC power modules can be exploited to a larger extent in an SST configuration due to higher switching frequency which will lead to smaller sized magnetic components. Also, the required space for the cooling system / heatsinks can be significantly reduced due to improved thermal conductivity. All these can result in increased power density of the overall converter.

5 WIND FARM – REFERENCE USE-CASES

In this chapter, we will explore the state of the art in wind farm topology and wind turbine design, as well as the definition of reference use-case topologies and wind turbines.

We will begin by examining the latest developments in wind farm topology, including the inter-array system, export infrastructure, and site condition trends. The inter-array system refers to the arrangement of wind turbines within a wind farm, while the export infrastructure is responsible for transmitting the generated power to the grid. We will also discuss the latest trends in site conditions.

Next, we will explore the motivation for larger wind turbines, including their potential to increase energy production, reduce the cost of energy, and improve overall efficiency. We will discuss the latest advancements in blade technology, power electronics, and control systems, as well as the challenges associated with scaling up wind turbines.

We will then define the reference use-case topologies for wind farms, including small/medium, large, and very large wind farms. These reference topologies provide a standardized framework for wind farm design and operation.

Finally, we will define the reference wind turbine, representative of the wind turbines to come and which will serve as a base line to compare alternative solutions.

5.1 WIND FARM TOPOLOGY STATE OF THE ART AND TREND ANALYSIS

5.1.1 *Inter-array system*

The wind farm internal electrical infrastructure, also known as the IAC for "inter-array cables" grid, collects the energy produced by the wind turbines and connects it to the wind farm's high-voltage transformer station onshore or now mainly offshore .

The architecture and technologies employed must meet a global technical and economic optimum with numerous constraints and challenges:

- **The investment cost** (CAPEX) essentially linked to the supply and installation of the electrical equipment (inter-array submarine cables and equipment at the foot of the turbines),
- **The operating cost** (losses, maintenance) (OPEX)
- **Availability** (reliability, redundancy, etc.) to limit the risk of loss of production in the event of damage.
- **Cable robustness**, impacted by various parameters
- **Other factors** more specific to the marine environment linked to the nature of the seabed or the constraints of coactivity in the maritime domain (exclusion zone, no crossing of cables, pre-existing submarine infrastructures, etc.).

This set of constraints determines the topologies and the electrical equipment that enable an overall technical and economic optimum to be reached. The maximum cable section is limited by the manufacturing and the installation process thus limiting the current and at the same time the power. A limited power will decrease the number of turbines that can be chained with a single cable so at

the end, increasing the turbine size is pushing higher the voltage that needs to be used in the inter-array system.

The voltage level used within the inter-array system in the farms currently in operation is in the medium voltage range, typically 33 kV AC. The new wind farms will have a high voltage of 66 kV in order to meet the increase in the unit power of the wind turbines (around 10 MW). It is expected that next inter-array voltages will reach over 100 kV by 2030, and 132 kV seems likely to be the next rated voltage level.

Of the very many possible topologies for connecting wind turbines to each other, the topology that currently dominates is the simplest, essentially radial topology with a few branches.

The wind turbines are connected in series, usually 5 to 10 units, on the same link, the whole forming a so-called "string" or "feeders". This simple topology minimises CAPEX (limiting the total length of submarine cables). Other topologies with a certain amount of redundancy are possible (topologies with looping between two strings, for example), improving availability in the event of damage, but with a higher investment cost.

The increase in power considered for wind turbines and farms motivates the development of alternative topologies to improve the availability of the internal collection grid and thus limit the estimated loss of production over the lifetime of the farm. But the simplest natural path is to consider higher voltage levels for the inter-array system. After 33 kV, then 66 kV, the 132 kV level is already being considered as the output voltage by some wind turbine manufacturers to comply with the expected future power ratings around 20 MW

The 20 MW wind turbine will be considered as the reference rated power for our reference use-cases.

As a rule of thumb, considering a standard cross-linked polyethylene (XLPE) submarine cable cross-section of 1200 mm² copper, a 33 kV string is limited to 45 MW of power, 66 kV string is limited to 90 MW and, as a projection, 132 kV string should be limited to 180MW. 1200 mm² is retain as a reference and as the maximum cross-section that can be considered even if this large cross section is a challenge with regards to the cable accessories.

The power and ampacity capabilities do not consider extensive optimisation or accurate sizing regarding the laying and environmental conditions, cable length, power factor or voltage drop, etc. Instead, are considered reasonably representative hypotheses for fair benchmark purposes between AC and DC inter-array grid systems.

Typically, the ratings are considered with a three-core cable configuration submarine cable – copper conductor with a burial depth around 1 m (soil temperature of 20°C, soil thermal resistivity 1.0 K.m/W) as usually given in supplier datasheets.

Table 11 –String limitations relative to 20 MW turbines

Wind Turbine power	Inter-array system voltage	Power limitation per string	Typical number of turbines in the string
20 MW	33 kV	45 MW	2
	66 kV	90 MW	4
	132 kV	180 MW	9

Table 11 shows the summary of string limitations relative to 20 MW turbines and different voltage levels of inter-array systems. The typical number of turbines in the string is calculated according to the power and simplified hypotheses.

The cables used for the inter-array system must comply with current and rated voltage levels. Table 12 below shows the current ratings for available three-core submarine cables with steel wire armour.

Table 12 -Current rating for three-core submarine cables [3]

Cross-section (mm ²)	Copper conductor (A)	Aluminium conductor (A)
92	300	235
120	340	265
150	375	300
185	420	335
240	480	385
300	530	430
400	590	485
500	655	540
630	715	600
800	775	660
1000	825	720
1200*	875	764

**: extrapolated data from smaller cross sections*

The Table 13 indicates the maximum power levels for strings for different inter-array voltages. It shows that 33 kV inter-array voltage is inadequate for the 20 MW turbines, from the topology viewpoint. The 66 kV inter-array voltage could be considered for the higher cross-sections, it is theoretically possible to construct strings with 4 wind turbines of 20 MW (for copper and 1000+ mm²). Finally, the 132 kV array seems to be the adequate choice from the topology point of view since it can host up to 9 turbines per string.

Table 13 – Maximum power and number of turbines per string with respect to cable cross section and inter-array voltage

Cross section (mm ²)	Inter-array voltage (kV)	Maximum power for copper (MW)	Maximum power for aluminium (MW)	Maximum number of WT for copper cables	Maximum number of WT for aluminium cables
92	33	15	12	0	0
150	33	20	15	1	0
240	33	25	20	1	1
630	33	37	31	1	1
1000	33	42	37	2	1
1200	33	45	40	2	2
150	66	39	31	1	1
240	66	49	40	2	2
630	66	74	62	3	3
1000	66	85	74	4	3
1200	66	90	79	4	3
300	132	109	88	5	4
630	132	147	123	7	5
800	132	160	136	8	6
1000	132	170	148	8	7
1200	132	180	157	9	7

5.1.2 Export infrastructure

The export infrastructure allows all the energy produced by the offshore wind farm to be exported to the onshore substation.

The architecture and technologies selected also meet a technical and economic optimum with a set of constraints similar to that of the inter-array system in terms of CAPEX, OPEX, environmental and regulatory constraints. However, in the case of the export and connection infrastructure, there are additional constraints linked to the high level of power to be transmitted from the farm, the distance to the shore and to the onshore substation, as well as the requirements of the grid codes.

This leads today mainly to the following types of schemes, as shown in

Figure 18:

- a) **Infrastructure without offshore substation:** For smaller farms (less than 100 MW), with parallel strings, that are not far from the shore (less than 15/20 km), this infrastructure is the simplest and consists of exporting the energy to the substation directly with the inter-array system without an offshore substation.
- b) **Infrastructures with offshore HVAC substation:** For larger farms (200 to 600 MW), with parallel strings, located less than 50/80 km from the shore and the substation, a high-voltage transformer station is installed on an offshore platform as close as possible to the farm. Its purpose is to step-up the voltage level so that the total production of the farm can be exported to land with limited electrical losses and fewer connections. Typical voltages used range from 132 kV to 245 kV. One or more submarine links are used to export the generation to the onshore substation. Each link consists of a single three-core cable, similar to the inter-turbine cables, but larger and with a water barrier screen, imposed by the higher voltage level of the HVAC export cables. Each link descends from the substation to the

seabed in a J-tube, then is buried at a depth of 1 to 2 m, where the seabed permits, otherwise fixed and protected by various devices (concrete mats, riprap, etc.) until it is landed on the coast. A landfall junction allows the connection and transition between the subsea part and the land part of the link, which continues as a conventional underground cable to the connection station. This scheme corresponds to a majority of the offshore wind farms installed today with a typical power of around 500 MW.

- c) **Export infrastructure with HVDC substation:** For the most remote offshore wind farms, beyond a limit distance of around 50 to 80 km (called "break-even distance") and of significant size (larger than 600 MW), HVAC export is no longer technically and economically interesting. It is then necessary to use high voltage direct current (HVDC) to export the production, which allows the transmission losses reduction and lower costs. It is then necessary to install an HVDC conversion substation at sea near the farms. The export link consists of a bipolar HVDC cable system, configured as a bundle to simplify installation (the two cables of both polarities are attached and laid together in one operation). The structure of the HVDC cable is similar to that of an HVAC cable. The main insulation of HVDC cables, which used to be oil impregnated paper in the mass, is now synthetic (XLPE) up to 320 kV. Above this value (525 kV or 640 kV), synthetic insulation is just beginning to be offered by the industry.

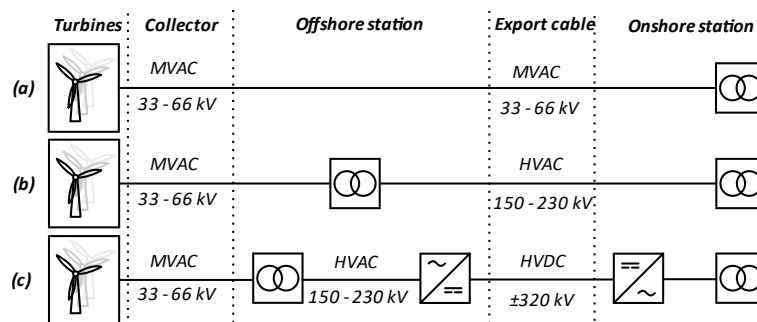


Figure 18 – Today's offshore wind farm export systems

5.1.3 Site condition trend

As can be seen from the graph below, the size of the wind farms tends to increase as they move further from the coast. This is due to the evolution of the maturity of the industry, the availability of new sites (outside the US and China) and of course the search for better wind spots. Furthermore, it is also observed that the LCOE decreases with the size of the wind farms, pushing the trend towards an increase in the size of the wind farms.

This can lead to three main typologies of wind farms:

- Small/Medium farms, between 250 and 400 MW, often less than 50 km from the shore
- Large wind farms, between 600 and 900 MW, found both less than 50 km from the shore (US, China) and more than 50 km from the shore (more in Europe where the closest sites have already been exploited)
- Very large wind farms, over 1GW, are often more than 50 km from the shore.

As regards the depth, it remains below 60 meters, which still allows to consider a bottom fixed installation. Examples of installed projects characteristics are shown in Figure 19.

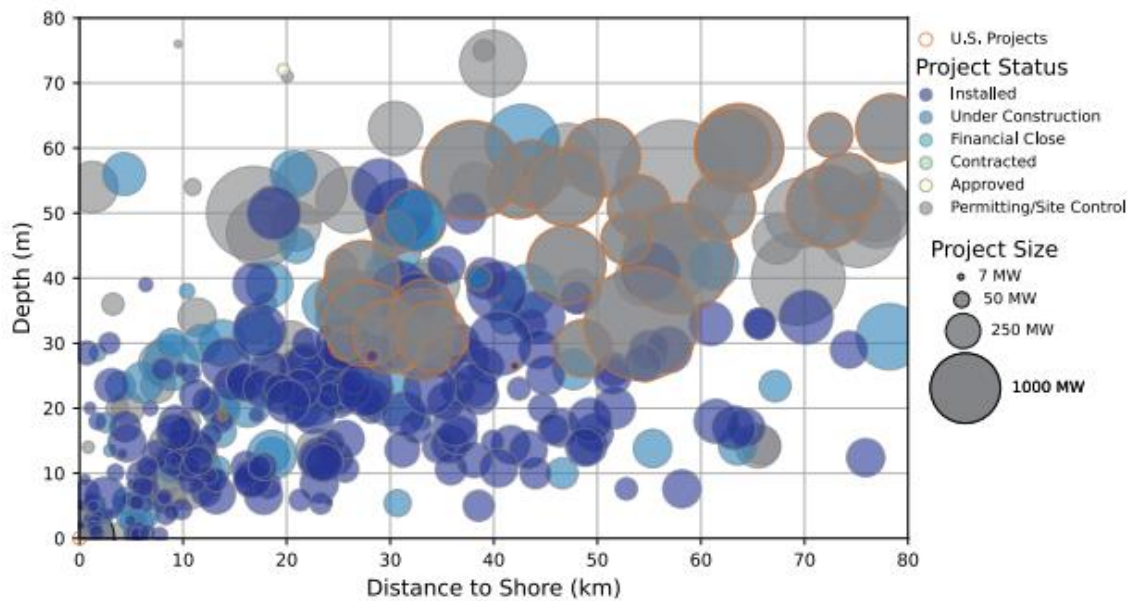


Figure 19 - Global fixed-bottom offshore wind energy project depths and distances to shore [7]

5.2 WIND TURBINES STATE OF THE ART AND TREND ANALYSIS

5.2.1 Motivation for larger wind turbine

The first offshore pilot farms were equipped with onshore wind turbines adapted to the marine environment (protection against corrosion and humidity). As reliability and performance were not sufficient, manufacturers developed environment-specific models. The technologies of direct drive generators or generators with a medium rotation speed (200 to 300 rpm), equipped with a more compact and more reliable gearbox (so-called "hybrid" conversion chain), have gradually become established (increased performance, better reliability, reduced maintenance, etc.). These conversion chains use synchronous generators with permanent magnets. It is the increase in the number of pairs of poles in the generators that allows them to reduce their speed of rotation, with the consequence that their diameter and weight increase.

As the unit power and rotor size of a wind turbine are the two key parameters for cost reduction in the industry (reduction of installation costs and times due to the reduction of the number of turbines, better load factor), turbine manufacturers have endeavoured to develop and market increasingly powerful and large wind turbine models, going from 2 to 3 MW (100-120 m rotor diameter) at the beginning of the 2000s, to 5-6 MW (150 m diameter) around 2010, then 8 to 10 MW (160 to 180 m diameter) at present.

The latest models currently on the market are moving to a new stage with 12-15 MW of power for a rotor diameter of 220-236 m, as shown in Figure 20. 20 MW seems to be the next target by 2030, or even 30 MW by 2050.

As stated before, for our use-cases, we will retain the 20 MW rated wind turbine.

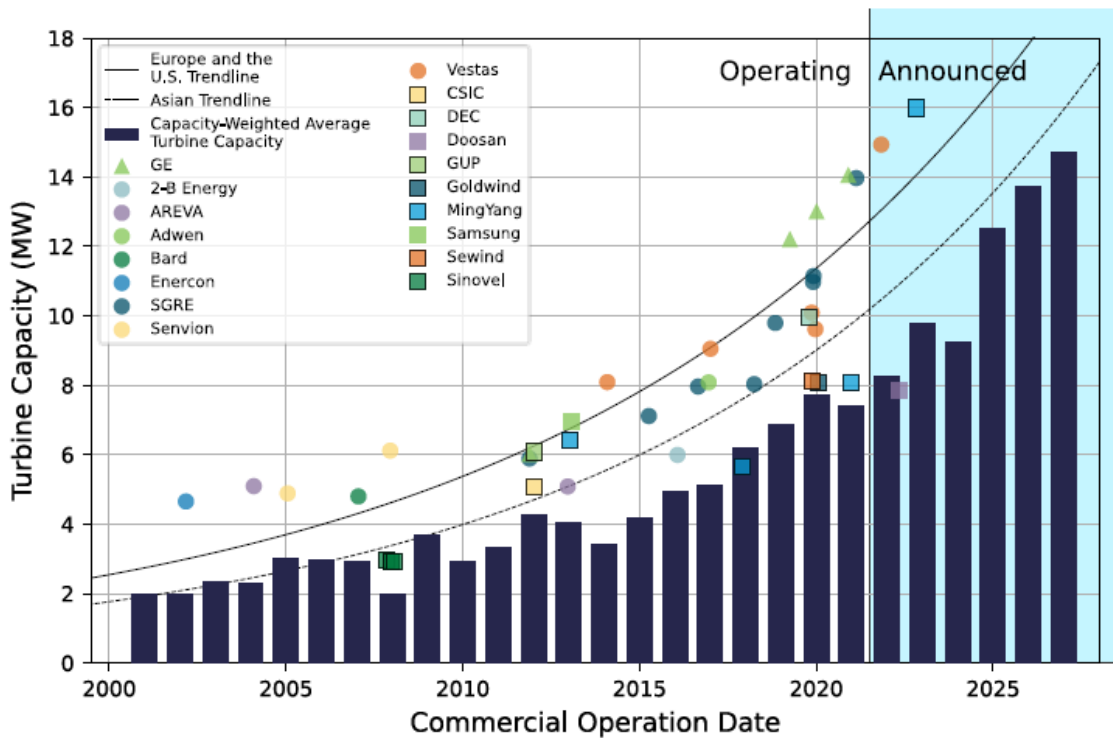


Figure 20 - Comparison of offshore wind turbine prototypes with commercial offshore turbine growth [7]

5.2.2 Generators and Conversion Chains

The generator is one of the most important components of wind turbines. The most common types of generators are explained here.

To recover the maximum energy from the wind in a horizontal axis wind turbine, it is necessary to maintain a blade rotation speed proportional to the wind speed. This is how variable speed wind turbines now operate in the range of wind speeds between start-up and the speed at which nominal power is reached. The current variable speed wind turbines can be classified according to the "conversion chain - generator" couple:

- type of conversion chain: either speed multiplier or direct drive;
- type of generators:
 - o asynchronous (or induction) generators, equipped with a squirrel cage rotor or a wound rotor (technology now more used in offshore wind) and
 - o synchronous generators with permanent magnet rotors (dominant technology in offshore) or wound rotors (essentially in onshore).

The following paragraphs will summarise the low and medium speed technologies.

- **Direct drive and synchronous generator technology (low speed):** These systems do not include a gearbox and the generators operate at very low speeds (due to a high number of pole pairs) with high torque. For the offshore wind sector, these generators are of the synchronous type with a permanent magnet rotor, offering better performance (increased efficiency) and inducing a much more compact but heavier nacelle. The alternator operates

at variable speed, and this implies a variable voltage and frequency output, hence the need to use a power conversion device to inject power into the grid which is at constant voltage and frequency. Typically, bidirectional AC-DC-AC voltage converters are used, consisting of an AC/DC converter operating as a rectifier that achieves optimal control of the alternator torque and a second DC/AC converter that operates as an inverter and controls the active and reactive power injected into the grid. In offshore wind, General Electric and Siemens Gamesa have made this technical choice, in particular for their latest models GE Haliade-X-14MW and Siemens-Gamesa SG 14-222; the Chinese company Goldwind offers this technology for its offshore wind turbines under 10 MW.

- **Multiplier and synchronous generator technology (medium speed):** The so-called "hybrid" conversion architecture corresponds to conversion chains where a single ratio gearbox is used with a permanent magnet synchronous generator to increase its speed (> 80 rpm). The generators used are also multipole machines, but more compact, due to the higher speed and lower torque compared to direct drive systems. The design of the gearbox is simpler and more robust and allows for integration with the alternator. The "hybrid" concept was initially proposed by the German manufacturer Aerodyn and applied to Areva turbines (Multibrid 5 MW, Adwen 8 MW). It is the choice of Vestas for its offshore wind turbines, including the future V236-15MW model, and of the Chinese manufacturers MingYang (MySE 16.0-242) and Goldwind, the latter adopting this technology for its next large offshore wind turbines (> 10 MW). It is expected that in the next decade offshore wind turbines will reach 20 MW of unit power with rotors of the order of 270 to 280 m in diameter. The optimal choice of the conversion architecture depends on many parameters: investment cost, required performance, ability to provide system services, availability, reliability and maintainability of the equipment, weight limitations of the nacelle and blades, and cost of materials including market tensions.

One of the future development paths to further increase the power of wind turbines while reducing the weight of the nacelle is the use of superconducting generators. The European EcoSwing project (2015-2019), in which Jeumont Electric was a partner, tested a 3.6 MW superconducting wind turbine. The use of superconducting materials as a substitute for copper considerably reduces the resistance of electrical circuits (current density multiplied by 100) but requires cryogenic cooling of around -240°C. GE has announced a prototype of the 17 MW Haliade-X for mid-2023, equipped with a superconducting generator. Voltage-producing copper coils will rotate inside an outer ring of fixed superconducting coils, made from a titanium-niobium alloy, which will generate a strong magnetic field. A summary of the different generator types is given in Figure 21.

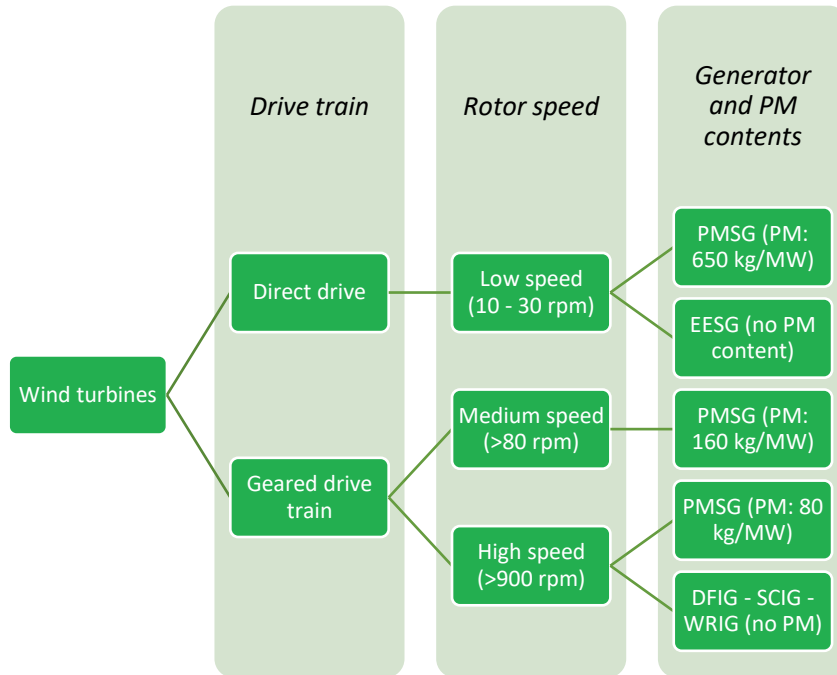


Figure 21 – Summary of different generator types used in wind power plants
(PMSG: permanent magnet synchronous generator; EESG: electrically excited synchronous generator; DFIG: doubly fed induction generator; SCIG: squirrel cage induction generator; WRIG: wound rotor induction generator)

5.3 REFERENCE USE-CASE TOPOLOGIES

Considering the trends and the state of the art previously established, we propose to retain as reference cases the three cases detailed in the following subsections, representative of the typologies of offshore wind farms to come and which will serve as a base line to compare alternative solutions.

The hypotheses for HVAC cables which will be considered are summarised in Table 14 below:

- three-core AC submarine cable – Trefoil formation – Both ends earthed – Cable in ground
- cross-section of 1200 mm² - copper - 875 A max current rating

Table 14 – Power transmission capacity for AC cables

		HVAC (kV AC)	
		245	275
Transmitted power (MW)	1 three-core 3x1000 mm ²	315	350
	2 three-core 6x1000 mm ²	615	700
	1 three-core 3x1200 mm ²	335	375
	2 three-core 6x1200 mm ²	670	750

5.3.1 Small/Medium Wind farm 260-600 MW

The first proposed reference use-case is a small/medium wind farm not too far from the coast, allowing for an HVAC export link, as shown in Figure 22.

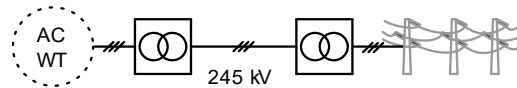


Figure 22 – Small/Medium wind farm reference case: export

The system consists of:

- 13 to 30 wind turbines of 20 MW
- A 66 kV or 132 kV inter-array cable system
- An HVAC offshore substation allowing to increase the voltage to 245 kV
- An HVAC onshore substation connected to the main grid with one (260 MW) or two (up to 600 MW) links
- A 50 km export link
- The wind turbines are 2.5 km apart (5 times their rotor diameter, assuming a blade length of 250 m for 20 MW wind turbine)

Possible configurations for this first reference use-case are shown in Figure 23.

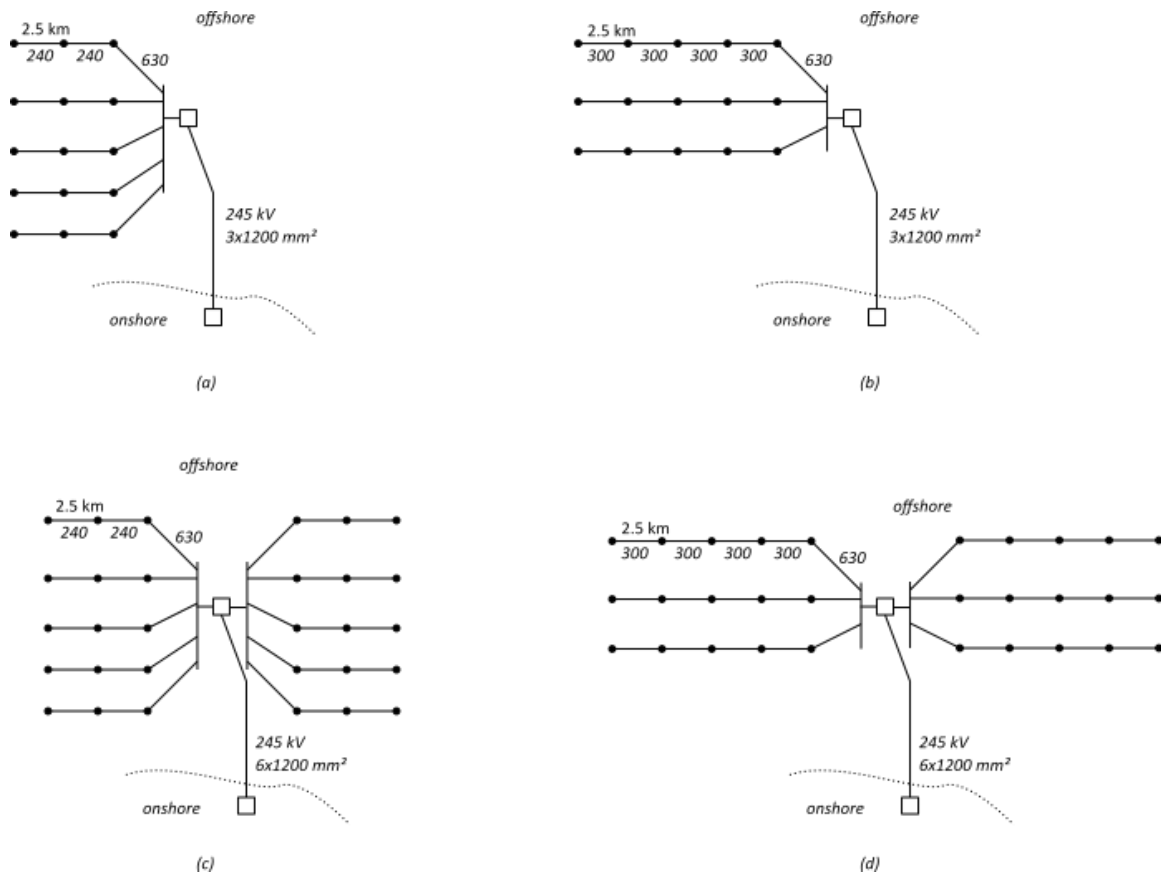


Figure 23 - Small/Medium reference case: inter-array system

- (a) 300 MW farm, 66 kV inter array voltage, (b) 300 MW farm, 132 kV inter array voltage, (c) 600 MW farm, 66 kV inter array voltage, (d) 600 MW farm, 132 kV inter array voltage

5.3.2 Large Wind farm 900-1200 MW

The proposed reference use-case is a large wind farm far from the coast, requiring HVDC export link, as shown in Figure 24.

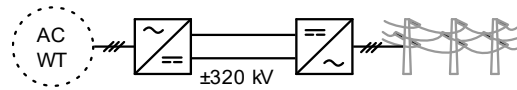


Figure 24 – Large wind farm reference case: export

The farm consists of:

- 45 to 60 wind turbines of 20 MW
- A 66 kV to 132 kV inter-array cable system
- An HVDC offshore substation allowing to increase the voltage to ± 320 kV
- An HVDC onshore substation connected to the main grid
- A 100 km export link
- The wind turbines are 2.5 km apart (5 times their rotor diameter)

This configuration of an offshore farm is representative of the modern large-scale wind farms and is shown in Figure 25 for 66 kV and 132 kV inter array voltages.

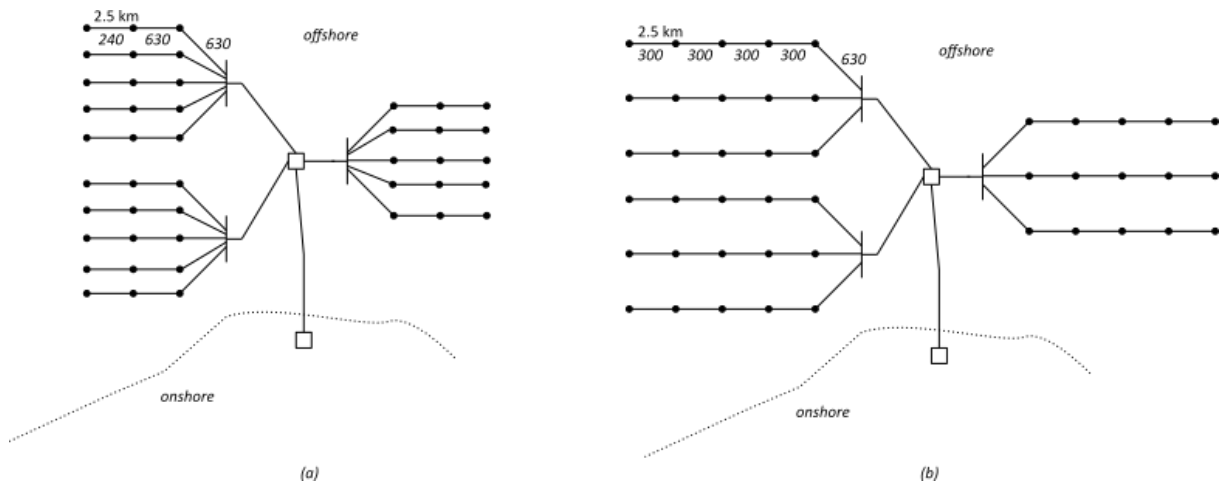


Figure 25 – Large wind farm reference case: inter-array
(a) 900 MW farm, 66 kV inter array, (b) 900 MW farm, 132 kV inter array

5.3.3 Very large wind farm 1.2-2 GW

The third proposed reference use-case is very large offshore wind farm (1.2 GW+), as shown in Figure 26.

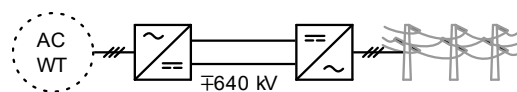


Figure 26 -Very large wind farm reference case: export

The farm shown in Figure 27 consists of:

- 60 to 100 wind turbines of 20 MW

- A 132 kV inter-array cable system
- An HVDC offshore substation allowing to increase the voltage up to ± 640 kV
- An HVDC onshore station connected to the main grid
- A 100 km export cable with a diameter to be determined
- The wind turbines are 2.5 km apart (5 times their rotor diameter)

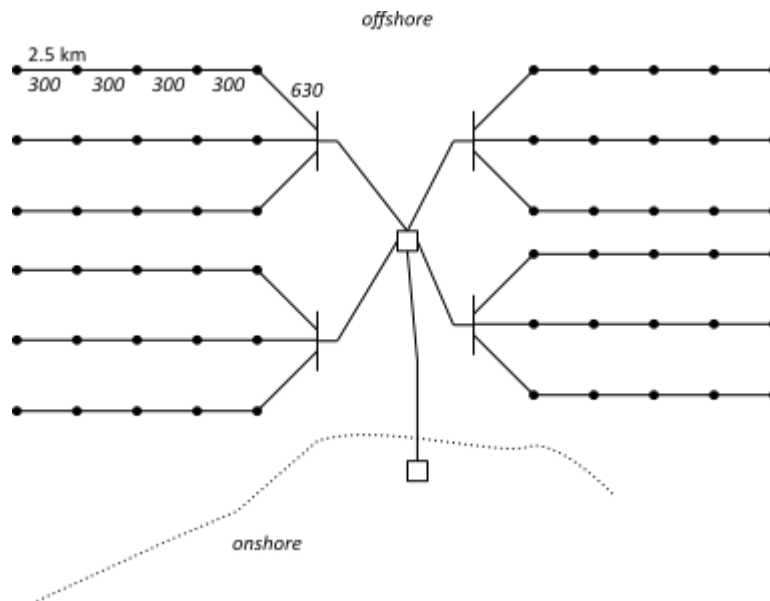


Figure 27 -Very large wind farm reference case: inter-array
1.2 GW, 132 kV inter-array

5.4 REFERENCE WIND TURBINE RATINGS

Considering the trends and the state of the art previously established regarding the wind turbines, we propose to retain as reference case the following one, representative of the wind turbines to come in the future and which will serve as a base line to compare alternative solutions.

The output voltage of the generator is expected to be in the range of 690 V, 3.3 kV, 6,6 kV (or even higher) voltages given the larger power rating considered. The AC/DC converter is connected back-to-back to a DC/AC converter, serving as a mean of control of the generator. The transformer steps up the voltage to 66 kV or 132 kV.

This turbine specification is used for the inter-array systems previously explained.

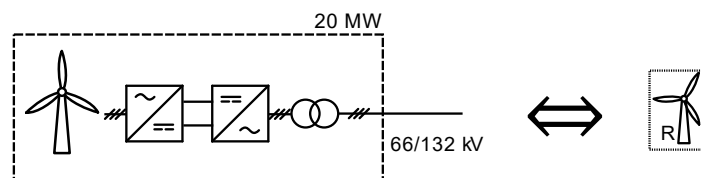


Figure 28 – Reference wind turbine case (left) and its symbol (right)

We assume that the drivetrain consists of a PMSG (Permanent magnet synchronous generator) delivering 690 V or 3.3 kV. We will also consider alternative drivetrains able to deliver higher medium voltages.

6 WIND FARM – ALTERNATIVE HVDC/MVDC CONCEPT ANALYSIS

This chapter presents different alternative DC wind farm concepts. Firstly, different native DC turbines are discussed and compared in terms of topology. Then, some indications on the maturity of different components composing a DC turbine are addressed. Secondly, alternative HVDC/MVDC topologies are discussed and compared.

6.1 ALTERNATIVE DC WIND TURBINE

6.1.1 DC Wind Turbine concept overview

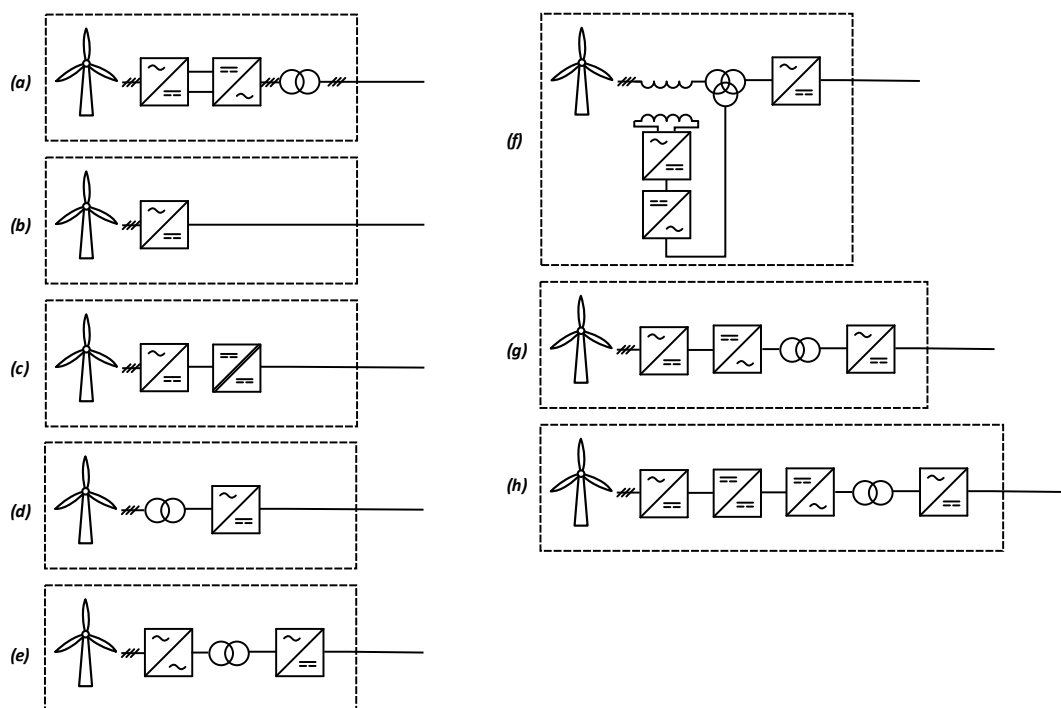


Figure 29 - Different DC wind turbine concepts

Several DC wind turbine concepts are proposed in the literature, Figure 29:

- Today usual AC wind turbine concept
- One stage conversion with an active rectifier. The advantage here is a low number of components and simplicity. On the other hand, there is no galvanic isolation and the turbine output is limited by the generator voltage.
- The second concept proposes the use of DC/DC converter in series with the rectifier allowing the increase of the voltage to a higher level.
- The third concept proposes the transformer in series with a passive rectifier (but without the DC/DC converter). Here again, the solution is simple and necessitates a low number of components. However, this solution lacks flexibility
- The fourth concept proposes the use of matrix converters.
- The fifth concept proposes a 3-stage concept limiting the disadvantages of the third concept.

- g) The sixth concept is a 4-stage concept that uses an active rectifier, inverter, power transformer and a high-power DC/DC converter. This allows the voltage to reach higher level whilst providing the galvanic isolation.
- h) The seventh concept proposes a use of a boost converter between the rectifier and inverter.

6.1.2 DC Wind Turbine analysis benchmark

Most of the components that make up a DC wind turbine are considered immature at an early stage of application. Table 15 below summarizes the maturity of DC wind turbines components.

Table 15 – Technology readiness level of key technologies for DC wind turbines [8]

	TRL	Maturity	Comment
DC turbine integration	3	Immature	Limited progress. Low market interest
Generator	9	Mature	Well-known technology
AC/DC converter	8-9	Semi-mature	Technology is possible but not applied to DC turbines
DC/DC converter	3-4	Immature	Technology is possible but not yet demonstrated
DC switchgear	7-8	Early stage	Technology is possible

As one can see, the DC wind turbines have some progress to do to attract more interest from the market. Most of the technology is possible, but a further work on its demonstration and application is needed.

6.2 ALTERNATIVE HVDC/MVDC TOPOLOGIES

To cope with the increasing power of wind turbines and offshore wind farms, one of the possible routes considered is to increase the rated voltage of the inter-array grid. This has typically been done by increasing the voltage from 33 kV to 66 kV AC and probably soon to 132 kV.

Another possible route, more disruptive, would be to use medium voltage direct current (MVDC) that can ease to transmit higher power.

In addition to reduced losses and the need for fewer cables (two-core system instead of three-core), the ability of direct current to transport energy over long distances could avoid, in certain configurations, the installation of HVAC substations at sea, the so-called "platformless" concept. However, MVDC grids remain an R&D topic, which assumes the availability of wind turbines designed to natively deliver MVDC. In addition to multiple possible topologies associating in series or parallel the different MVDC buses, these MVDC grids bring important constraints, or even technological locks: MVDC circuit breaker for a real selectivity in case of fault, DC/DC converters, ...

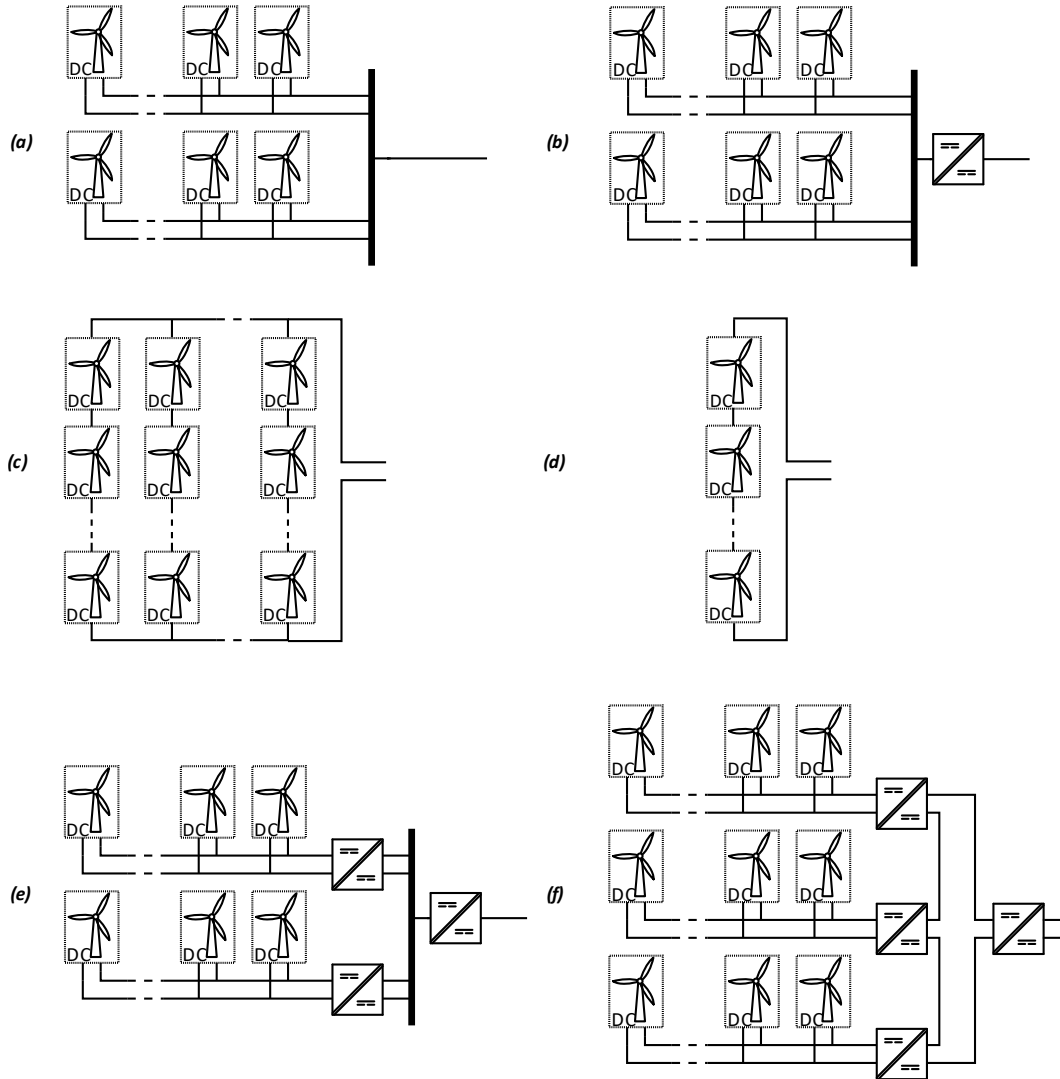
There is a plethora of MVDC/HVDC topologies, relying on multiple DC/DC solutions⁴ that can lead to "platformless" concept, but with various degrees of complexity and maturity.

There are several designs that have been proposed in the literature for the MVDC/HVDC inter-array systems. The simplest one, similar to AC radial inter-array system, consists of a parallel connection

⁴ Several DC/DC solutions have been investigated. For example, the offshore wind farm power flow is directed towards the shore, it is possible for the DC/DC converters to be unidirectional (isolated and non-isolated) [10].

of native DC wind turbines. The voltage is then stepped up using offshore DC/DC converter substation. Otherwise, there are many series-parallel associated configurations [9].

The overview of DC inter-array wind farms configurations is illustrated in Figure 30.



*Figure 30 - Overview of alternative inter-array topologies with DC wind turbines
 (a) Radial without an offshore platform, (b) Radial with an offshore platform, (c) Series-parallel, (d) Series single loop, (e) Parallel topology with split step up, (f) Series-parallel radial topology with submodules*

As shown, there are many possibilities for the constitution of MVDC/HVDC collector systems using the DC wind turbine concepts. Here, the solutions are qualitatively analysed in Table 16 using several criteria.

Table 16 – Comparison of different inter-array topologies

	A <i>Radial without an offshore platform</i>	B <i>Radial with an offshore platform</i>	C <i>Series-parallel</i>	D <i>Series single loop</i>	E <i>Parallel topology with split step up</i>	F <i>Series-parallel radial topology</i>
Advantages	No need for an offshore platform Most similar to AC radial inter-array system, reduced technological risk	Lesser losses in the HVDC export cable Most similar to AC radial inter-array system, reduced technological risk	No need for an offshore platform Lesser losses in the HVDC export cable	No need for an offshore platform Same cable in the whole loop Lesser losses in the HVDC export cable	Lesser losses in the HVDC export cable Simpler WT drive train that can be just a 50 Hz transformer with an active or passive rectifier	Possibility of higher flexibility in terms of control and operation of the wind farm Lesser losses in the HVDC export cable
Disadvantages	Higher losses in the MVDC export cables (due to the lower DC voltage achievable at WT scale and multiple export cables)	Need for a dedicated offshore platform for DC/DC conversion and voltage step-up	Challenging control and operation in balancing the voltage Reduced efficiency High vulnerability to failures Need to manage WT insulation to ground	Challenging control and operation in balancing the voltage Reduced efficiency High vulnerability to failure Need to manage WT insulation to ground	Complicated / multiple offshore platform Lower efficiency as the turbine yields are controlled at the string level	Numerous DC/DC converters and complex architecture

When discussing the MVDC alternative topologies for the inter-array cable systems, it is worth to look at the “equivalent” voltage and power ranges of the inter-array, as detailed in Table 17.

Table 17 – Power and voltage ranges of the inter-array systems [10]

Inter-array AC voltage	33 kV	40 kV	66 kV
Inter-array “equivalent” DC voltage	±50 kV	±60 kV	±100 kV
Power per inter-array feeder	40 – 60 MW	50 – 80 MW	80 – 130 MW

Hypotheses for DC cables, whose power transmission capacity is summarised in Table 18 and Table 19:

We limit ourselves here to a maximum of 3 bi-poles, i.e. 3x2 cable cross-section, in order to remain comparable with AC cables where typically we export with two three-core links, i.e. 2x3 cable cross-sections. This makes it possible to compare in all cases more or less with a same total cable cross-section, and therefore same amount of copper or aluminium. But from the laying operation point of view, 2 routes vs 3 routes, this is not fully comparable.

The power and ampacity capabilities of the cable given below do not take into account extensive optimisation or accurate sizing regarding the laying and environmental conditions. Instead, are considered reasonably representative hypotheses to achieve a fair benchmark between AC and DC inter-array grid systems.

Typically, the ratings are considered with a close laying bundle configuration: Bi-pole submarine cable – copper conductor – Cable with a burial depth around 1 m (soil temperature of 15°C, soil thermal resistivity 1.0 K.m/W) as usually given in supplier datasheets.

Table 18 - Power transmission capacity for DC cables

	Cross-section	MVDC/HVDC (+/- kV DC)						
		40	60	80	100	120	140	160
Transmitted power per bi-pole (MW)	bi-pole 2x1000 mm ²	105	150	210	255	300	355	405
	bi-pole 2x1200 mm ²	115	170	230	285	345	400	460
	bi-pole 2x1600 mm ²	135	200	270	335	400	470	535

Table 19 – Submarine ampacity capabilities for considered cross-sections

Submarine DC cable		
Cross-section (mm ²)	Copper conductor (A)	Aluminium conductor (A)
95	340	250
240	580	430
630	1000	720
1000	1250	1000
1200	1450	1100
1600	1700	1290

The findings in [8] indicate the maturity level of different technologies. The cables have been considered as a mature technology since they are commercially available.

The most critical components in the MVDC collector systems are the DC/DC converters, that are not commercially ready yet for the MV and HV applications. We can mention also that the DC switchgears (DC circuit breaker) remain not completely commercially available.

The academic research supports the development of DC array technology. The industry breakthrough is awaited in the coming years if the progress in terms of TRL continues.

7 WIND FARM – ALTERNATIVE MVDC/HVDC USE-CASE DEFINITION (SPECIFICATION, REQUIREMENTS)

This chapter aims to provide an overview of alternative MVDC/HVDC use-cases for wind farms, as well as the specification and requirements for these systems.

7.1 ALTERNATIVE TOPOLOGIES

Taking into account the analysis of alternative concepts previously established, we propose to retain as alternative use-cases in the project the following three cases, which make it possible to respond to the different typologies of reference farms.

These alternative use-cases are also retained because they present the best potential to take advantage of the benefits expected from the use of DC technologies. These benefits are expected to be internal to the farm's collection grid with copper savings and less Joule losses, but above all, on the export infrastructure with the opportunity to remove the need for an offshore substation.

The choice of the inter-array and turbine output DC voltage will be the result of a trade-off within the project developments. Indeed, the DC voltage that can be generated by a wind turbine is subject to limitations related to what is economically and technically feasible at the scale of the wind turbine.

But on the other hand, it is in the interest of having a sufficiently high DC voltage to limit the cable cross-section and in particular to consider a direct export to the shore without the need to go through an offshore substation.

Remark: the different use-cases presented below are given as examples to illustrate the problematic. The inter-array rated voltage (± 40 kV to ± 160 kV), number of wind turbines and specific configuration shall be determined according to the optimisation in WP2, considering the global trade-off relative to rated powers, rated voltages, and cable cross-sections, among other constraints.

7.1.1 Small/Medium wind farm – Use-case 1

We consider here the case of farms with a capacity of about 260 to 600 MW, as shown in Figure 31.

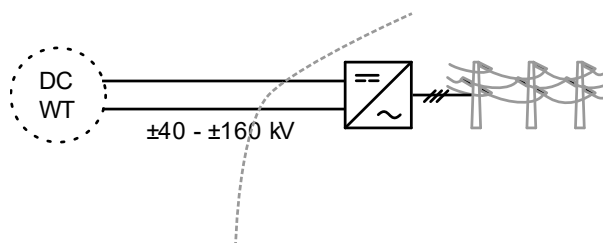


Figure 31 - Small/Medium wind farm use-case: export

The encircled DC WT block represents the inter-array grid system.

This case is particularly interesting in relation to the use of DC technologies because it presents the characteristics compatible with a direct export scheme to the coast with the inter-array grid system

with no need of an offshore substation. Only an HVDC converter station is located onshore allowing the conversion from DC to AC.

The Figure 32 shows two examples of small/medium farms of 300 MW and 600 MW with an inter-array rated voltage of ± 40 kV. At this rated voltage, three bi-pole ± 40 kV – 1000 mm^2 export links are enough, whereas the 600 MW requires multiple bi-pole export links, even if a higher cross-section, like 1600 mm^2 can save one bi-pole export link in that case.

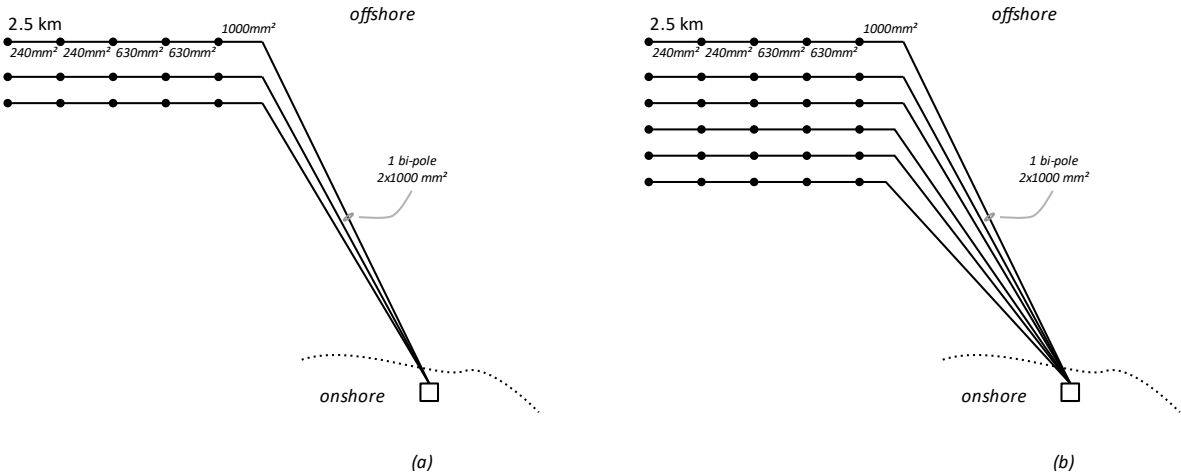


Figure 32 – Examples of Small/Medium MVDC wind farms: inter-array
 (a) 300 MW, ± 40 kV – 1000 mm^2 inter array, (b) 600 MW, ± 40 kV – 1000 mm^2 inter array

Otherwise, it is possible to use a two bipolar export system where the clusters of wind power plants would be arranged as in theFigure 33. In this case, according to the values in the Table 18 and Table 19, the inter-array and export voltage should ± 120 kV with two 1000 mm^2 export bi-pole links. It is also possible to consider ± 100 kV inter-array and export voltage with two 1600 mm^2 export bi-pole links as an alternative.

This is a use-case on the verge between small/medium and large wind farms.

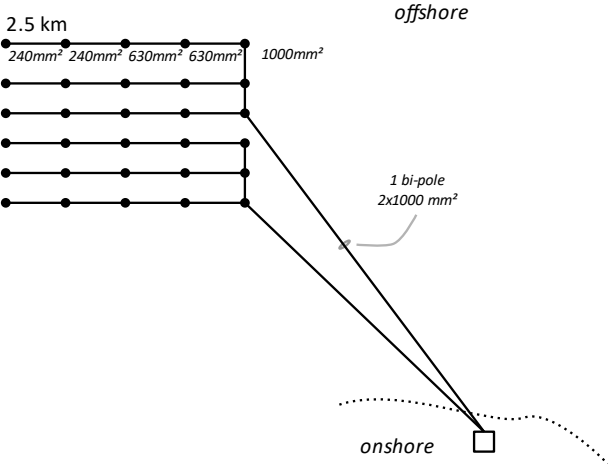


Figure 33 – Example of a Small/Medium wind farm: inter-array
 600 MW, ± 120 kV – 1000 mm^2

7.1.2 Large Wind farm – Use-case 2

We consider here the case of farms with a capacity of between 900 and 1200 MW, as shown in Figure 34.

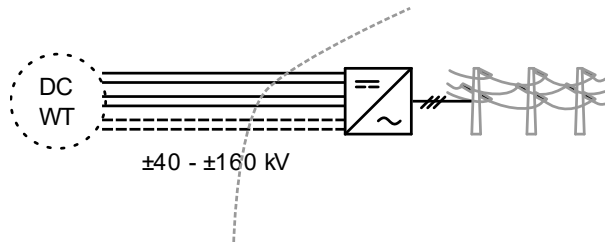


Figure 34 - Large wind farm use-case

This case is a little bit more challenging due to the higher power to be evacuated, which implies doubling the number of export links compared to the previous case.

The Figure 35 shows an example of a large wind farm use-case:

- a) Wind farm contains 45 DC wind turbines grouped into three clusters of 15. The voltage used for the export and for the inter array is ± 120 kV, as defined in the Table 18 and Table 19. Three ± 120 kV – 1000 mm² bipolar links are used for export, as illustrated. It is also possible to consider ± 100 kV inter-array and export voltage with three ± 100 kV – 1600 mm² bipolar links as an alternative.
- b) Wind farm contains 60 DC wind turbines grouped into three clusters of 20. The voltage used for the transport and for the inter array is ± 160 kV, as defined in the Table 18 and Table 19. Three ± 160 kV – 1000 mm² bipolar links are used for export, as illustrated. It is also possible to consider ± 120 kV inter-array and export voltage with three ± 120 kV – 1600 mm² bipolar links as an alternative.
- c)

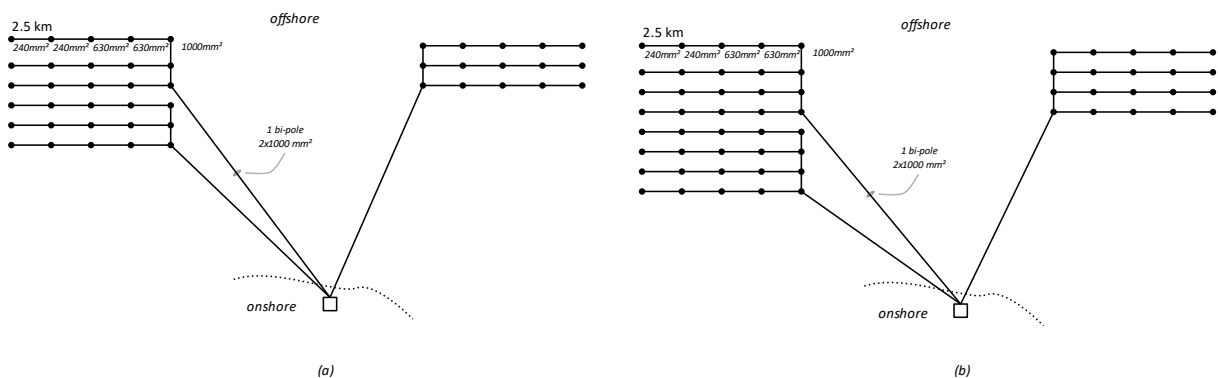


Figure 35 – Example of a Large wind farm use-case: inter-array
(a) 900 MW, ± 120 kV – 1000 mm² inter-array, (b) 1200 MW, ± 160 kV – 1000 mm²

7.1.3 Very large Wind farm – Use-case 3

We consider here the case of farms with a capacity of around 1.2 to 2 GW, as shown in Figure 36.

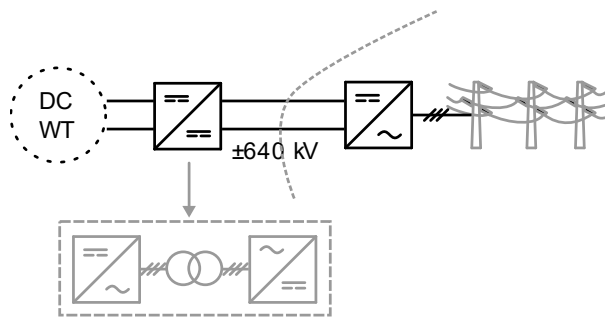


Figure 36 – Very large wind farm use-case: export

This case is very challenging due to the large power to be evacuated, with multiple export links compared to the previous case if we stay in the same range of DC voltages.

Also, it may be necessary here to seek to step up the DC voltage level for export to shore. For this, it may be considered to use an offshore DC/DC substation, but this option has the major disadvantage of reintroducing the need for an offshore substation which removes most of the interest of considering DC technology for the inter-array grid system.

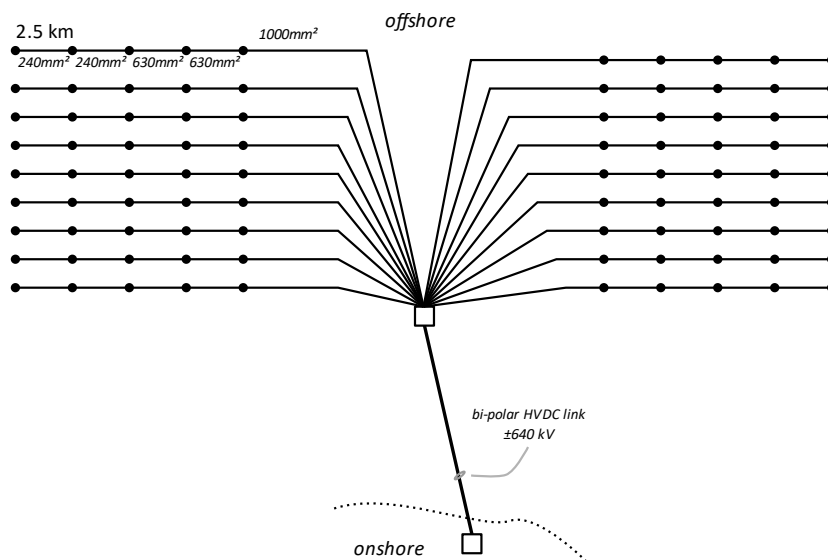


Figure 37 – Example of a Very large wind farm use-case: inter-array
 2 GW, ± 40 kV – 1000 mm² inter-array voltage
 ± 640 kV HVDC link (bi-pole + metallic return) between the offshore and onshore substations

Another possibility might be to consider alternative serial/parallel association topologies of the different feeders in the inter-array grid system to build a higher DC voltage for export to the shore.

In this alternative topology, it is then possible to consider again a lower DC voltage for the internal inter-array grid system as ± 40 kV DC or ± 60 kV DC but this will come at the expense of greater complexity as discussed in a previous section.

7.2 FIRST DC ALTERNATIVE WIND TURBINE (SiC BASED MMC - DRU CONVERTER)

Current wind turbine converter technology is dominated by low-voltage Si-based semiconductors in two or three level converters, having DC link voltage around $1000 V_{dc}$.

With the development of the new multi-MW wind turbines with medium voltage output, new converter topologies and semiconductors are needed with higher voltage ratings and better switching/conduction characteristics. Both topics are addressed in this project, firstly by developing MV voltage rated SiC MOSFET based power modules (3.3 kV and 800A), competitive with the classical Si-based ones and secondly, advanced converter topologies will be analysed and tested like Multi Modular Converters (MMC) and Solid-State Transformers (SST), using the advantages of the SiC technology (better heat management, smaller cooling and magnetic components, bigger power density, etc.).

A first alternative wind turbine to be considered is a wind turbine allowing to address the first two use-cases where we have an interest in having the highest possible DC voltage, typically in the range of 80 kV to 160 kV. This DC wind turbine is shown in Figure 38.

Because of this relatively high DC output voltage, we will choose a wind turbine whose rectifier in charge of generating the high DC voltage will be of a technology allowing a certain compactness compatible with its installation in a wind turbine.

Therefore, we will use a Si based DRU (Diode Rectifier Unit) type technology for the rectifier and its step-up transformer, as shown in Figure 40.

For the AC/AC converter, whose input and output voltages remain in the medium voltage range, the converter topology will be of the classic MMC (modular multilevel converter) type in a back-to-back configuration, as shown in Figure 39.

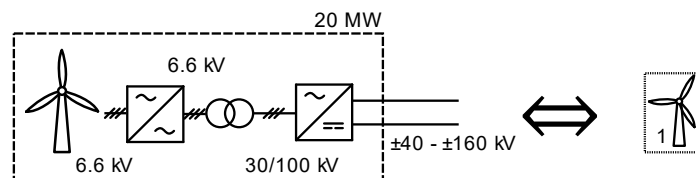


Figure 38 – First DC wind turbine use-case

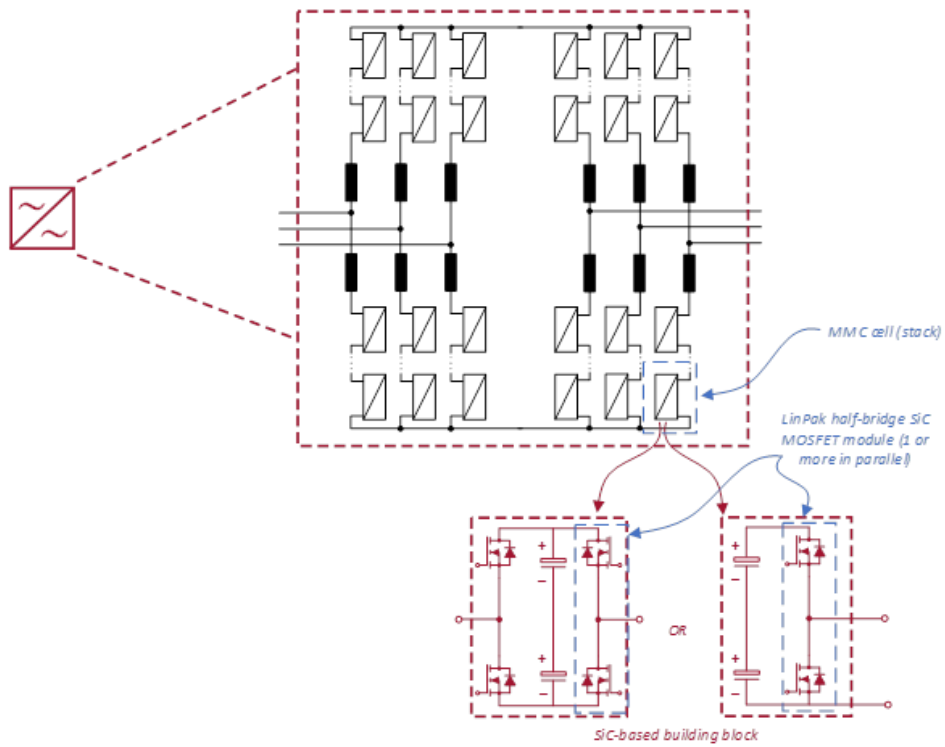


Figure 39 - AC/AC Unit - MV side - MMC

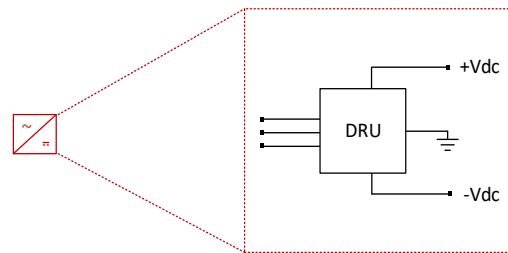


Figure 40 – AC/DC unit – HV side - DRU

7.2.1 MMC converter level requirements

For the first converter alternative, the MMC converter, a specification as outlined in the Table 20 is suggested.

Table 20 -Specification of the MMC converter

Property	Value	Comment
Electrical Properties		
Input/Generator voltage	6.6 kV	Higher voltage TBC
dV/dt	<1.5kV/ μ V	Match to requirements of generator
Output voltage	6.6 kV	Equal to input voltage in MMC
Output frequency	50..250Hz	Aligned to design of step-up transformer and DRU
Output quality	TBD	Match to requirements of step-up transformer and DRU
Power rating, nominal	20 MW	
Overload rating	+10% 2s pr 60s	
Mechanical Properties		
Size	TBD	Depends on placement in WT
Weight	TBD	Depends on placement in WT
Environmental Properties		
Temperature, ambient	0..40°C	Operational conditions without derating
Humidity	<95% RH	
Vibration	TBD	Depends on WT requirements
Functional Properties		
Machine side control		Control for MV PM synchronous generator
Output side control		Near sinusoidal output matching step-up transformer and DRU
Fault ride through		TBD
Protection features		TBD

Some of the requirements must be quantified in unison with the design of the full power-train generator and step-up transformer/DRU. Each WT manufacturer also has particular requirements for their mission-profiles and are therefore to be determined.

7.2.2 Characteristics of the SiC based MMC converter

To meet the requirements set forth in the preceding section and to take advantage of the properties of SiC this section proposes architectures for converter-implementations.

SiC allows for increasing the cell voltage in comparison to a LV IGBT based cell. The benefit is to either decrease the required number of cells to reach a specified converter voltage or the meet a higher voltage requirement without increasing the number of cells. The latter is the approach taken here.

The higher current carrying capability of SiC will reduce the required number of parallel power-modules to meet a certain arm current. In general, reducing the number of parts in a system improves reliability. However, it also impacts the redundancy of parallel modules negatively, which to some extent will counter the improved reliability/availability of the converter. Conversely the number of parallel modules can be kept equal to the standard IGBT solution and provided the losses of the SiC-MOSFET are kept low the arm-current can be increased significantly leading to a better utilization of the converter. (Increased power density Power/m³). Another advantage of the MOSFETs over the IGBTs is the positive on-resistance characteristic. It improves the MOSFETs paralleling and stable current sharing capability.

As the MMC is inherently a *low-frequency* converter due to the increased number of levels, the benefit of SiC's high-frequency switching capabilities is not as pronounced as in other converter-

types. However smaller gate-charge requirements will ease the burden on the gate-driver and in this way impact both reliability and cost positively.

Some calculations for the MMC converter using SiC power modules rated to **3300 V** and **800 A** with regards to current handling:

$$V_{ac_rms} = 6600 \text{ V}$$

$$P = 20 \text{ MW}$$

$$I_{ac_rms} = \frac{P}{V_{ac_rms}\sqrt{3}} = 1750 \text{ A}$$

$$I_{ac_peak} = I_{ac_rms}\sqrt{2} = 2475 \text{ A}$$

Conclusion: Still need 4 x 800 A modules in parallel

7.3 SECOND DC ALTERNATIVE WIND TURBINE (SIC BASED SST CONVERTER)

For the second alternative DC wind turbine, we choose a wind turbine delivering a lower DC voltage in the range of 40 kV to 80 kV allowing to consider smaller converters and compatible with the space and weight constraints to be installed in a wind turbine, as shown in Figure 41.

This choice of DC wind turbine is compatible with the small wind farms close to the shore where the direct export with the inter-array grid system is still possible with a lower DC voltage, or for the very large wind farms inter-array grid system where an offshore DC/DC step-up station is installed to ensure export.

For the DC/DC converter, whose input is low voltage range and output is medium voltage range, the converter topology will be an SST in a multilevel configuration, as shown in Figure 42.

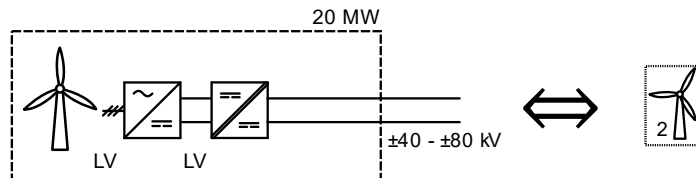


Figure 41 - Second DC wind turbine use-case.

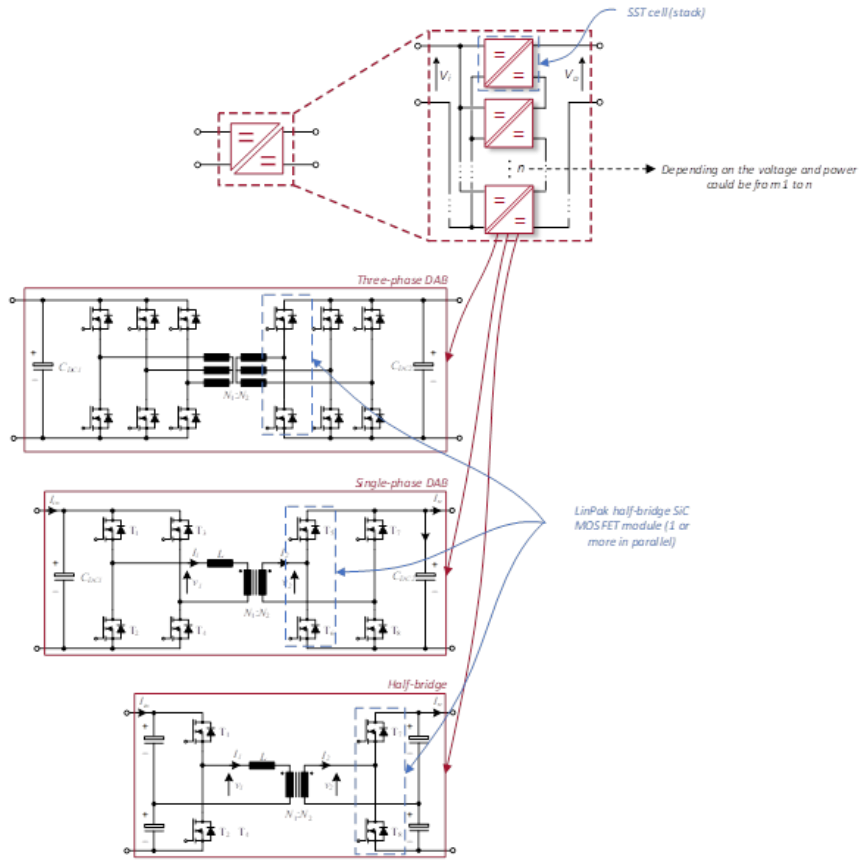


Figure 42 - LV/MV DC-DC converter structure

7.3.1 SST converter level requirements

The main building block of the SST converter is an isolated DC-DC converter. The galvanic isolation is obtained by medium frequency (from few kHz to few 10 kHz) transformers. With increased switching frequency the power density of these transformers can be reduced. The multiple number of these converters (cell), in various serial or parallel connections, give flexibility to adjust the delivered power and output voltage of the system.

Some calculations for the SST-based converter

As shown in Figure 41, the generator side AC/DC converter is a standard LV converter. We consider a standard LV DC link of this around 1200 V. In this case the DC link current at 20 MW will be:

$$V_{dc} = 1200 \text{ V}$$

$$P = 20 \text{ MW}$$

$$I_{dc} = \frac{P}{V_{dc}} = 16.6 \text{ kA}$$

If the two converters (AC-DC and DC-DC) are well integrated, the DC link is short, this does not represent a problem.

If we consider higher voltages (6.6 kV_{ac} on the generator side), the input DC link for the SST is approximately 10 kV_{dc}. In this case the calculations are as following:

$$V_{dc} = 10 \text{ kV}$$

$$P = 20 \text{ MW}$$

$$I_{dc} = \frac{P}{V_{dc}} = 2 \text{ kA}$$

This gives a good utilization in series and parallel connection of the newly developed SiC power modules, their voltage and current characteristics.

On the other hand, in the output stage (SST structure with serial connection on the MV side presented above) using SiC power modules rated to **3300 V** and **800 A**:

$$V_{dc_in} = 1200 \text{ V}$$

$$V_{dc_out} = \pm 40 \text{ to } \pm 80 \text{ kV}$$

$$\text{Allowed } V_{dc_out/module(cell)} = 2000 \text{ V (max)}$$

these constraints will result in an increased number of individual cells such as that require space, due to MV isolation criteria.

Another solution would be to replace the MV side switching MOSFETs of each cell with higher voltage rated SiC diodes (5+ kV). So the required output MV DC voltages can be more easily reached with a reduced number of modules (cells) connected in series. Here special attention should be made to the MF/HF transformer isolation criteria. Such way a modified and integrated DRU system is achieved, similarly to the concept presented in 7.2.

7.3.2 Characteristics of the SiC based SST converter

The advantages of SiC based power-modules in relation to the MMC converter, presented in 7.2.2 are valid also for an SST-based solution. Specifically, the switching performance of SiC power modules could be exploited to a larger extent in an SST configuration due to higher switching frequency which will enable smaller sized transformers.

8 CONCLUSION

In conclusion, this deliverable has presented a set of use-case scenarios for the SiC4GRID project, with the goal of defining realistic scenarios relevant to the use of silicon carbide (SiC) converters. The use-case scenarios cover a range of configurations in terms of type, size, and topology of renewable farms, with a focus on alternative MVDC/HVDC topologies using innovative SiC-based modules and converters.

The use-case scenarios were constructed based on a thorough review of relevant literature and project analysis, starting with a reference HVAC/MVAC use-case, and leading to the construction of HVDC/MVDC use-cases for both PV and wind farms. These scenarios provide a common baseline for the development of innovative and optimized solutions for the project and serve as a guide for the development of converters based on the same technological brick.

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