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Chapter 5

Definition of a Base Scenario

The objective of this book is the analysis of the key issues of the offshore wind farm's energy transmission and grid integration infrastructure by using a representative case. Thus, in the present chapter, a main scenario (base scenario) is defined. The evaluation starts with some generic features of the offshore wind farm, such as: the rated power and the distance to shore. Then, considering these generic features, the main elements of the offshore wind farm are characterized, based on the current state of the technology.

In this way, firstly the number of connections to shore and the transmission voltage level based on the economical optimum are selected (without considering the wind turbines). Thus, based on the developed submarine cable model, on specific location characteristics and specific cost estimations, the transmission cost for three different AC transmission configurations is calculated: single HVAC, various HVAC and MVAC. Then considering this estimated transmission cost, the most cost efficient lay-out is selected for a 150MW wind farm at 50 km to shore.

Once, the main electric connection structure is selected, a base scenario is developed for further analysis. To that end, the offshore wind farm's components are modeled and sized taking special care on wind turbines.

The wind turbines are considered a key issue. So, after the definition of their rated power, the control strategy and the grid side filter, the wind turbines are tested via simulation to verify that the defined wind turbines are suitable to place in an offshore wind farm and if they can fulfill the grid codes.

5.1 Wind farm's layout selection

As it has been concluded in chapter 3, to select the proper energy transmission solution, a specific analysis is needed. Therefore, in the present chapter by using a design procedure, based on the location characteristics and a proper reactive power management of the submarine cable of the chapter 4, the most cost efficient energy transmission solution is defined.

In the literature, several analyses about the energy transmission cost based on the produced energy are carried out [67], [68]. These studies are focused on the comparison between AC transmission and DC transmission options. More specifically, the analysis in [68] is based on very high rated powers 400-1000MW. These studies also do not consider in detail the reactive power compensation or different AC transmission options at different rated powers and voltages.

Therefore in this section, using a similar procedure, the cost for different lay-outs focused in AC configurations is estimated. More specifically, considering a wind farm of 150 MW in a location with 9m/s of average wind speed, the transmission cost for several AC lay-outs at different distances to shore is calculated.

5.1.1 Considered offshore AC layouts

There are several options to transfer the energy generated in an offshore wind farm to the distribution grid. These options range from the HVDC (High Voltage Direct Current) connection to various MVAC (Medium Voltage Altern Current) connections, section 3.2.

Considering AC connections, the different lay-outs are divided into two families: HVAC (High Voltage Altern Current) and MVAC connections. Within these two AC families, there are also different design options. These options are determined by the number of submarine cables to connect the offshore wind farm with the distribution grid and their voltage level, see section 3.2.1.

With regards to the number of connections to shore, the present evaluation has considered the following configurations: a unique connection of 150 MW, two connections of 75MW (2x75MW) and five connections of 30MW (5x30MW).

The voltage level is another important characteristic of the transmission system. Hence, several transmission voltages from medium voltage (36kV) to high voltages (150kV and 220kV) are taken into account in this evaluation. In this way, depending on the Nº of clusters and transmission voltage, the suitable cable is used.

In short, the considered AC configurations and their associated cable (

Cable	Vn (kV)	In(A)	Rac(Ω/Km)	L (mH/Km)	C (μF/Km)
A	36	911	0.0341	0.294	0.331
B	150	1088	0.0205	0.352	0.233
C	220	1055	0.048	0.37	0.18

Table 4.4) are summarized in Table 5.1. Moreover, a couple examples of these configurations are shown in Figure 5.2 and Figure 5.3.

Cable	*Electric configurations*
A	5x30MW-36kV
B	150MW-150kV / 2x750MW-150kV
C	150MW-220kV

Table 5.1 Cable used for each electric configuration.

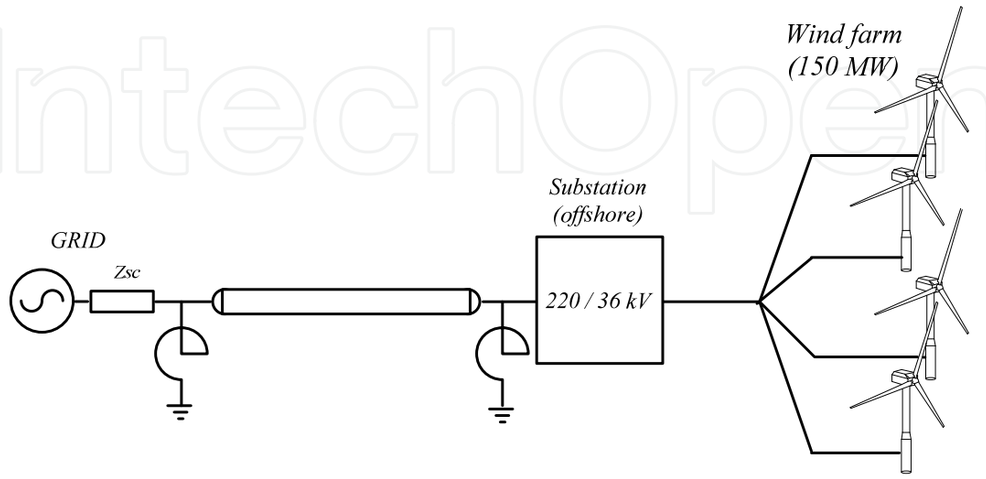


Figure 5.1 Electric configuration of a 150MW-220kV wind farm.

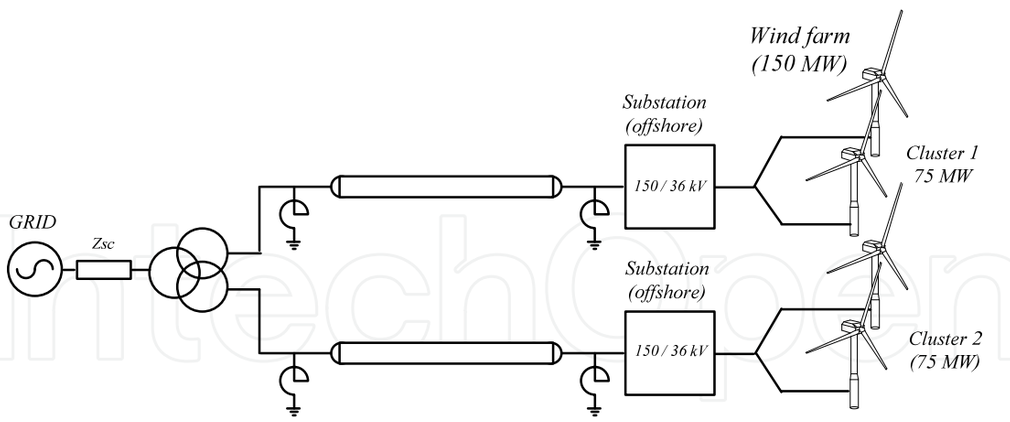


Figure 5.2 Electric configuration of a 2x75MW-150kV wind farm.

5.1.1.1 Considered submarine cable model

This evaluation is focused on the selection of the AC transmission lay-out for offshore wind farms. Therefore, the transient behavior of the transmission system has not been taken into account, i.e. the submarine cable has been modeled for steady-state operation.

Thus, the submarine cable has been modeled as a several "π" circuits in series (see section 4.2.2). Due to the fact that this model can represent the cable at steady-state and allows the results measure in intermediate points.

In this chapter, there are taken into consideration three different cables, the same ones of the previous chapter 4, as shown in Table 5.2.

Cable	*Vn (kV)*	*In(A)*	*Rac (Ω/Km)*	*L (mH/Km)*	*C (μF/Km)*
A	36	911	0.0341	0.294	0.331
B	150	1088	0.0205	0.352	0.233
C	220	1055	0.048	0.37	0.18

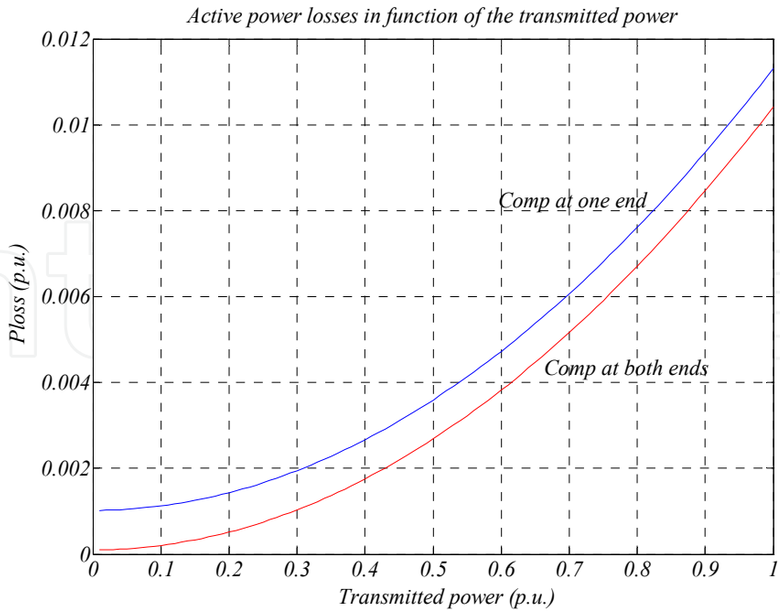
Table 5.2 Submarine cable characteristics.

5.1.1.2 Considered reactive power compensation

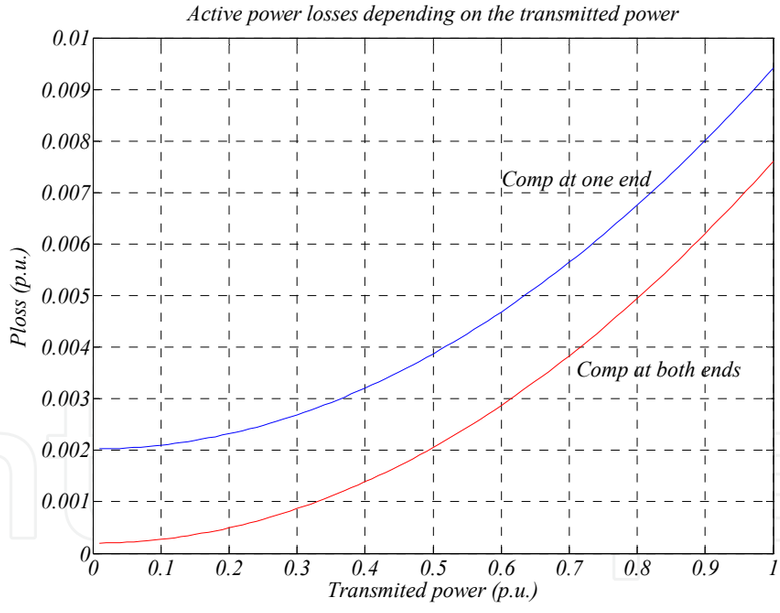
The reactive power management is an important variable to select a lay-out of the offshore wind farm: This is because with an inadequate compensation the cable can be unusable or causes an increase in conduction losses. Consequently, it is important to determine firstly the reactive power management.

This evaluation does not take into account the technological aspects of how the reactive power is compensated, only the way that it manages the reactive power through the cable. In this way, fixed reactive power compensation at both ends of the cable is considered to perform the management of the reactive power through the submarine cable, see section 4.3.3.

The reason for considering this kind of reactive power management for the submarine cables is because this kind of management reduces considerably the active power losses, at any transmitted power level and for all the layouts, as can be derived from Figure 5.3.



(a)



(b)

Figure 5.3 Active power losses for 50km cable length, with compensation at both ends (red) and onshore compensation (blue). (a) 150MW-150kV and (b) 150MW-220kV.

5.1.2 Procedure to calculate the energy transmission cost

As is explained previously, the main criteria to select the electric configuration of the offshore wind farm is economic [69].

Consequently, in this section, for a specific AC offshore wind farm, based on an approach of the cost of the transmission system elements (submarine cable cost, O&M cost...) and depending on these three variables: average wind speed, rated power and location. The most cost effective (economic optimum) lay-out is estimated.

Therefore, the number of cables to use in the transmission system, their voltage level and the characteristics of the offshore platform (if required) are defined. In short, the electrical lay-out.

Notice that the wind turbines are not considered in the present evaluation. The evaluation is focused on the transmission system lay-out, so a simplified model of the entire offshore wind farm is used to estimate the generated energy.

The block diagram of the procedure to calculate the cost of the energy transmission is depicted in Figure 5.4.

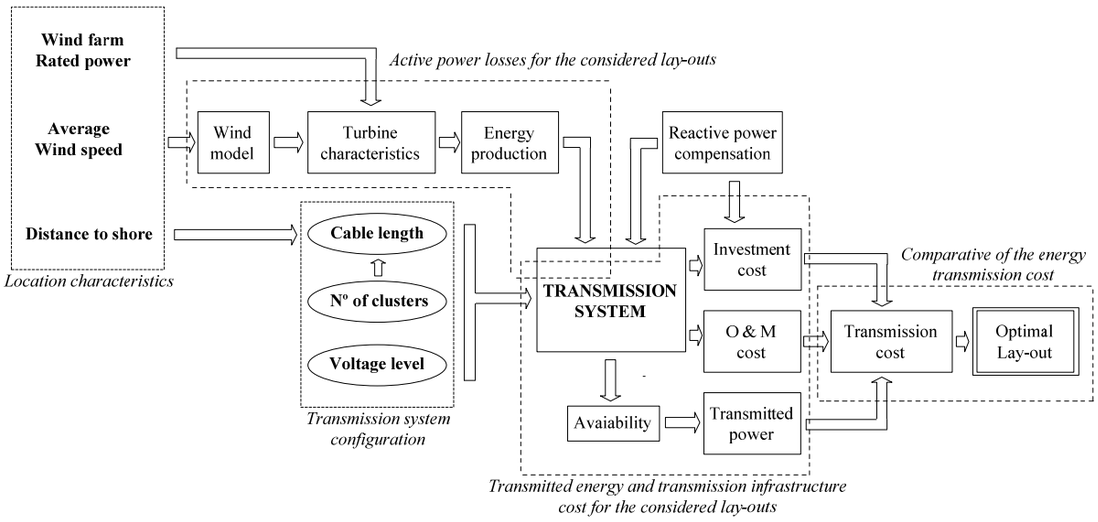


Figure 5.4 Block diagram of the procedure to select the transmission system lay-out.

Firstly, the reactive power compensation of the transmission system is defined (location and quantity). At the same time, the energy production at the offshore wind farm is calculated depending on the rated power of the wind farm and the average wind speed of the location.

In the next step, the active power losses of the transmission system are calculated considering the characteristics of the cable such as: the cable length, the transmission voltage and the transmitted power. The objective to calculate these average power losses is estimate the transmitted energy.

Finally, the transmission cost is defined as the investment cost (estimated operating and maintenance, O&M cost included) of the transmission system divided with the transmitted power. Therefore, energy transmission cost in €/kWh is obtained.

5.1.3 Active power losses for the considered lay-outs

Due to the fact that, the energy transmission cost is based on the relation between the investment cost and the generated energy, but measured in the PCC (after the transmission

system), active power losses in the transmission system are a very representative variable to design the transmission layout.

The average active power losses of the transmission system depends on four variables: wind farm's rated power, distance to shore, average wind speed and reactive power management

In the present evaluation, for a 150 MW wind farm with fixed reactive power compensation at both ends, four different configurations are considered.

With regards of wind speed, it can be treated as a continuous random variable. The probability that a wind speed shall occur can be described with a Rayleigh distribution, see section 2.1.2, equation (106).

$$R(v_{wind}) = \frac{k}{c} \cdot \left(\frac{v_s}{c} \right)^{k-1} \cdot e^{-\left(\frac{vs}{c}\right)^k} \tag{106}$$

Where: $R(v_{wind})$ is probability density, v_{wind} is wind speed (m/s), k is shape parameter (=2) and c is scale parameter.

The average wind speed is chosen from Figure 2.17, an average wind speed for a good location 9 m/s. The Rayleigh distribution for a 9 m/s average wind speed is shown in Figure 5.5.

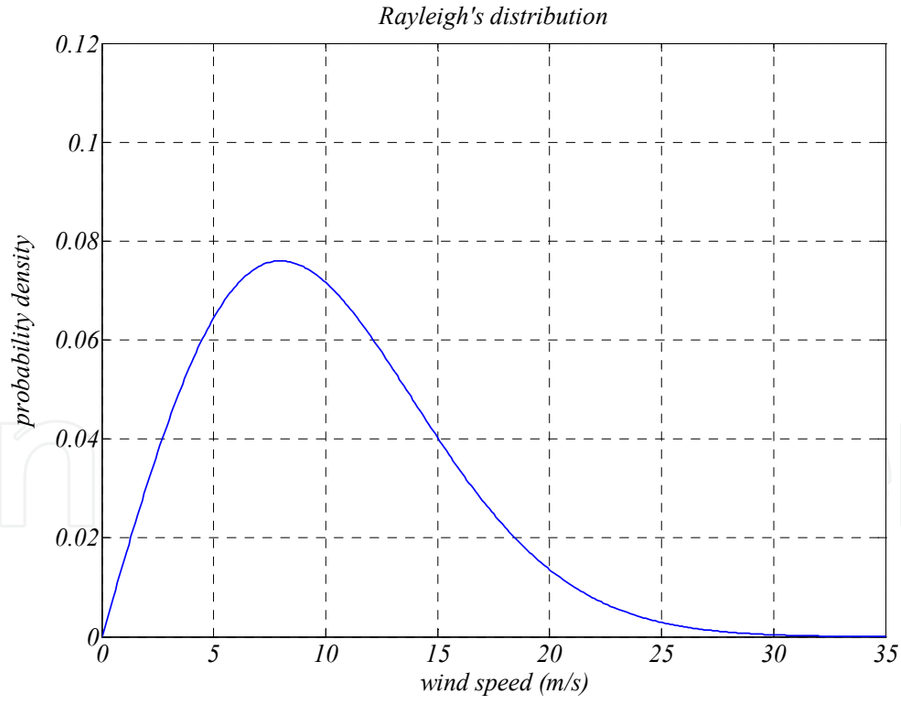


Figure 5.5 Rayleigh distribution for 9 m/s average wind speeds.

On the other hand, in equation (107), the active power produced on the wind turbine (see section 2.2.3) depending on the wind speed and turbine characteristics are calculated (Figure 5.6).

$$P_t(v) = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot V_{wind}^3 \cdot Cp \tag{107}$$

Where: $P_t(v)$=Generated power depending on the wind speed, ρ= air density (1.125 measured in kg/m^3), R=Wind turbine radio (126 m), V_{wind}=Wind speed, Cp= Aerodynamic efficiency.

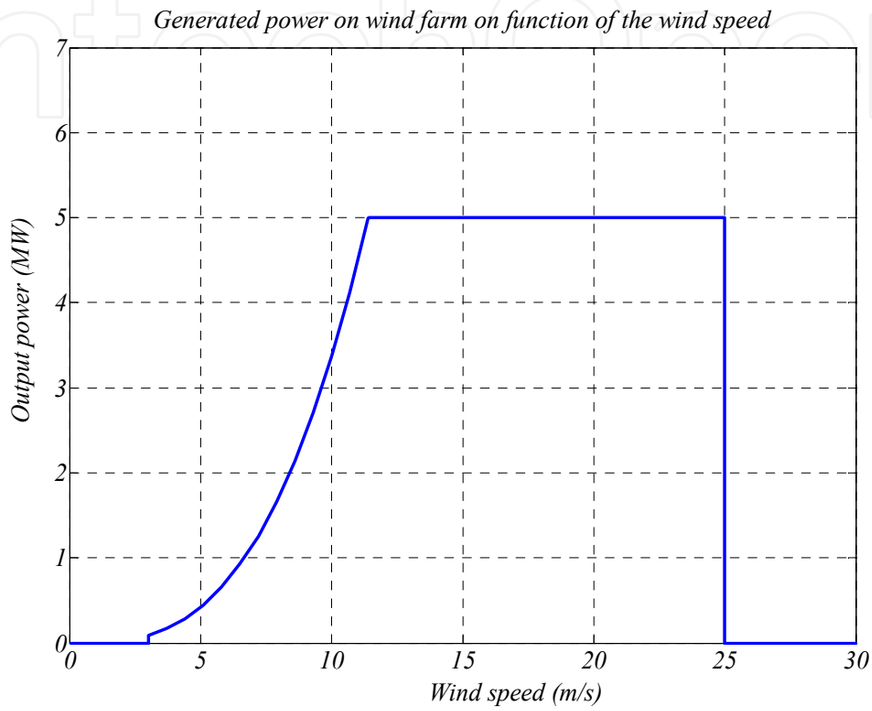


Figure 5.6 Generated power on the wind turbine depending on the wind speed.

Hence, considering the same average wind speed in all the 30 wind turbines (and the same probability density), it is possible to estimate the power generated in the wind farm and its probability density. As a result, it is also possible to obtain the produced average power, equation (108).

$$P_{avg} = \int_{Von}^{Vcut} P(v) \cdot Ry(v) \cdot dv \tag{108}$$

Where: P_{avg}=Average input power, $Vcut$= cut out wind speed (30m/s), Von= cut in wind speed (3,5m/s), $P(v)$=Input power depending on the wind speed, $Ry(v)$=probability distribution (Rayleigh).

This evaluation is focused in the transmission system, therefore losses in generators and losses in inter-turbine network have not been taken into account. Nevertheless, this simplification does not affects to the analysis, since these losses are the same for all the layouts and only affect to the amount of the produced active power.

Linking the active power losses of the submarine cable depending on the transmitted power level (Figure 5.3), with the produced active power depending on the wind speed (equation (102)). It is possible to obtain the active power losses depending on the wind speed, $P_{loss}(v)$. Finally, using the wind speed distribution probability, the average active power losses can be calculated, equation (109):

$$P_{loss_avg} = \int_{Von}^{Vcut} P_{loss}(v) \cdot Ry(v) \cdot dv \tag{109}$$

Where: P_{loss_avg}=Average active power losses, $Vcut$= cut out wind speed (30m/s), Von= cut in wind speed (3.5m/s), $P(v)$=Input power depending on the wind speed, $Ry(v)$=probability distribution (Rayleigh).

These losses depending on cable length for the considered AC configurations are illustrated in Figure 5.7.

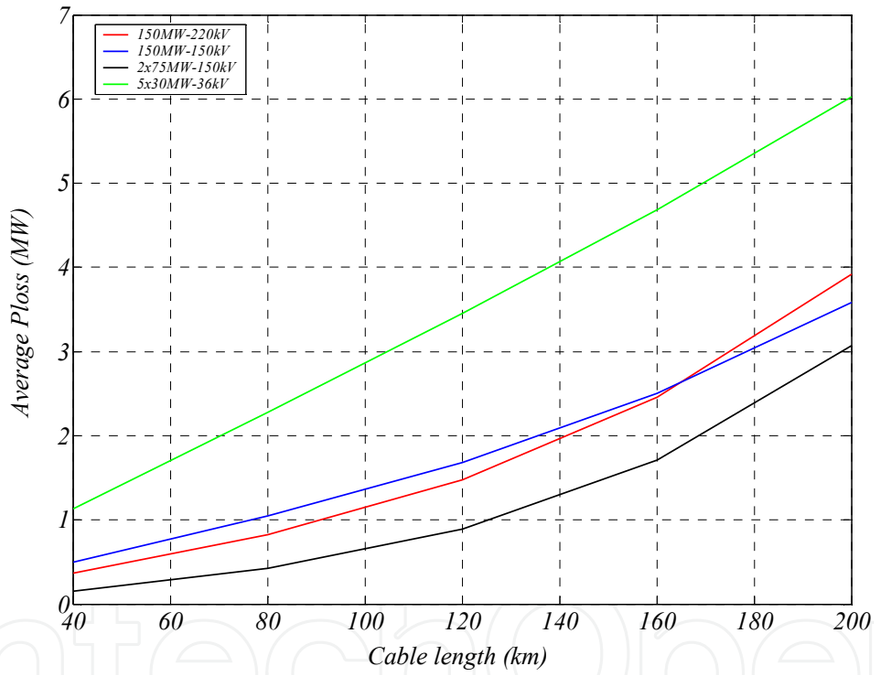


Figure 5.7 Average losses depending on the cable length for different lay-out configurations.

Due to the fact that the reactive power generated by the submarine cable has a quadratic relation with the transmission voltage (see section 4.3), increasing transmission voltage, not always conduction losses are reduced.

Looking at Figure 5.7, for cable lengths longer than 160 Km, the active power losses for 220kV configuration are bigger than the losses for the 150kV configuration.

5.1.4 Transmitted energy and transmission infrastructure cost for the considered layouts

Based on the estimation of the produced energy and the average losses of the transmission system, equations (108) and (109), it is possible to calculate the transmitted power through the transmission system for a determined life time.

Therefore, dividing this transmitted power with the sum of the investment cost and operating and maintenance cost, it is possible to obtain the energy transmission cost for the considered layouts.

5.1.4.1 Transmitted energy

The submarine cables have a failure rate, i.e. a statistical probability to occur a failure given by the manufacturer. In the present studio, the failure rate is considered 0,1/year/100Km [70]. In the same way, the mean time to repair (MTTR) is considered three months. So, based on this data, it is possible to estimate the availability of the submarine cables, equation (110).

In cases with multiple connections to onshore (wind farm divided into clusters) redundant connections between clusters are not considered. Because, as is reported in [41], the most of existing inter-turbine networks have very little redundancy or none at all. Consequently, the same availability of the cables is considered at the same distance to onshore as a simplification.

$$A_{cable} = \frac{t_{life} - f_{rate} \cdot \frac{l}{100} \cdot lt_{years} \cdot t_{repair}}{t_{life}} \tag{110}$$

Where: A_{cable} = Cable availability, t_{life} = Life time (month), f_{rate}=Failure rate (failure / 100 km / year), l=submarine cable length, lf_{years}= Life time (year), t_{repair}=MTTR (month).

The considered availability depending on submarine cable length is shown in Table 5.3.

	10km	***20km***	***40km***	***80km***	***120km***	***160km***	***200km***
Availability (20yrs)	0.9975	0.995	0.99	0.98	0.97	0.96	0.95

Table 5.3 Availability depending on submarine cable length.

For electrical configurations with offshore platform, it is also considered the availability of the step-up transformer. The failure rate is considered 0.03/year with 6 month of MTTR [71]. Therefore, the availability of the transformer can be estimated as follows:

$$A_{trafo} = \frac{t_{life} - f_{rate} \cdot lf_{years} \cdot t_{repair}}{t_{life}} \tag{111}$$

Where: A_{trafo} = Transformer availability, t_{life} =Life time (month), f_{rate}=Failure rate (failure/year), lf_{years}= Life time (year), t_{repair} =MTTR (month).

Finally, the transmitted energy is calculated, equation (112). The results for the considered layouts calculated with 9 m/s average wind speed and 20 years life time are summarized in Table 5.4.

$$E_{trans} = \left(P_{avg} - P_{loss_avg}\right) \cdot t_{life} \cdot A \tag{112}$$

Where: E_{trans} =Transmitted energy, P_{avg} =Average generated power, P_{loss_avg} =Average active power losses, t_{life} = Life time (h), A = Availability.

Transmitted Energy *(MWh)*	*10km*	*20km*	*40km*	*80km*	*120km*	*160km*	*200km*
150MW - 220kV	12909668	12861624	12764211	12556214	12317201	12025728	11658289
150MW - 150kV	12904426	12851165	12741316	12519127	12283552	12018159	11713215
2x75MW - 150kV	12918843	12879928	12802196	12626008	12417638	12151872	11798099
5x30MW - 36kV	12875852	12794161	12631263	12307169	11982751	11652341	11306269

Table 5.4 Transmitted energy for different configurations and lengths.

5.1.4.2 Cost of the connection infrastructure

With regards the cost of the connection infrastructure, in the present evaluation, the cost of the following elements are considered: transformer, offshore platform (if required), submarine cables, installation of submarine cables and reactive power compensators.

- Cost of the offshore platform, estimated at the same way that is done in [72].

$$C_{Plataform} = 2.14 + 0.0747 \cdot P_{rated} \tag{113}$$

$C_{platform}$ = Cost of the offshore platform (M€), P_{rated} = Rated power of the wind farm (MW)

- Cost of the transformer, estimated from equation (114) [68].

$$C_{transformer} = 0.03327 \cdot P_{rated}^{0.7513} \tag{114}$$

$C_{transformer}$ = Cost of the transformer (M€), P_{rated} = Rated power of the transformer (MVA).

- Cost of cable installation, this cost depends on the location of the wind farm and is difficult to estimate accurately. In this evaluation for cases with more than one line to connect to onshore, it is considered that all the submarine cables are installed together. The cost of the installation is estimated at 0.256 M€/Km [72].
- Cost of the submarine cables (estimation). This cost can have high fluctuations depending on the market.

	36kV	*150kV*	*220kV*
€/km	200.000	500.000	600.000

Table 5.5 Submarine cable cost.

- Cost of the static reactive power compensation [68].

$$C_{comp} = 0.02218 \cdot Q^{0.7513} \tag{115}$$

C_{comp} = Cost of the reactive power compensation (M€), Q = Reactive power to compensate (MVAR).

5.1.4.3 Cost of operating and maintenance

Maintenance of the submarine cables: The reparation costs are increasing and are strongly dependent on the market, due to the fact that a limited number of companies have the capability to install and repair submarine cables. However, in [73], the reparation cost for one XLPE 3-Core 132kV submarine cable is estimated on 3 M£ (3.3 M€) and the reparation cost for one XLPE 3-Core of 220kV to 400kV on 4.4 M£ (4.85 M€).

Thus, in the present section as an approximation, for submarine cables with voltages lower than 132kV (36kV) the reparation cost is considered 3.3 M€ and for submarine cables with voltages higher than 132kV (150kV/220kV) 4.85 M€. Therefore, the results for different cable length considering the failure rate of the submarine cables 0.1 / year / 100km and the life time 20 years is summarized in Table 5.6

***Nº of repairs** (20yrs)*	*10km*	*20km*	*40km*	*80km*	*120km*	*160km*	*200km*
150MW - 220kV	0.2	0.4	0.8	1.6	2.4	3.2	4
150MW - 150kV	0.2	0.4	0.8	1.6	2.4	3.2	4
2x75MW - 150kV	0.4	0.8	1.6	3.2	4.8	6.4	8
5x30MW - 36kV	1	2	4	8	12	16	20

Table 5.6 Estimated number of repairs in the life time of the cable (20 years) for different cables and cable lengths.

Maintenance of the offshore transformer: for the step-up transformer on the offshore platform a 0.03 / year failure rate is considered and the life time 20 years. As a result, the failure probability for each platform in its life time is 0.6. The reparation cost for these failures is considered 2.5 M£ (2.75 M€) from [71].

In short, considering the values of the previous sections, the required investment cost for different configurations and lengths are shown in Table 5.7.

Cost *(M€)*	*10km*	*20km*	*40km*	*80km*	*120km*	*160km*	*200km*
150MW - 220kV	25.2860	34.9340	54.1660	92.5830	130.9920	169.3490	207.7010
150MW - 150kV	24.2360	32.8490	50.0240	84.3430	118.6670	152.9460	187.2240
2x75MW - 150kV	29.9970	41.9420	65.8120	113.5160	161.1980	208.8660	256.5260
5x30MW - 36kV	15.9400	31.8550	63.6700	127.2700	190.8500	254.4200	317.9800

Table 5.7 Required investment cost for different configurations and lengths

5.1.5 Comparative of the energy transmission cost in €/kWh for the considered layouts

Considering that the invest cost is paid through the offshore wind farm's life time, the total invest cost (including financial costs) is calculated as follows [68]:

$$C_{invest} = \frac{rate \cdot (1 + rate)^{lf_{years}} \cdot lf_{years}}{\left((1 + rrate)^{lf_{years}} - 1\right)} \cdot Invest \tag{116}$$

Where: C_{invest} = Total investment cost, $rate$ = Interest rate (4%), lf_{years}= Life time (years), $Invest$ = Investment cost today.

Therefore, based on the energy generated and transmitted to the PCC (Table 5.4) and the estimated cost for each one of the transmission configurations (Table 5.7), the transmission

cost (€/kWh) is calculated, equation (117). Finally, the results for the considered layouts are shown in Figure 5.8.

$$C_{trans} = \frac{C_{invest}}{E_{trans}} \tag{117}$$

Where: C_{trans} = Energy transmission cost (€/kWh), C_{invest} = Total investment cost, E_{trans} = Transmitted energy.

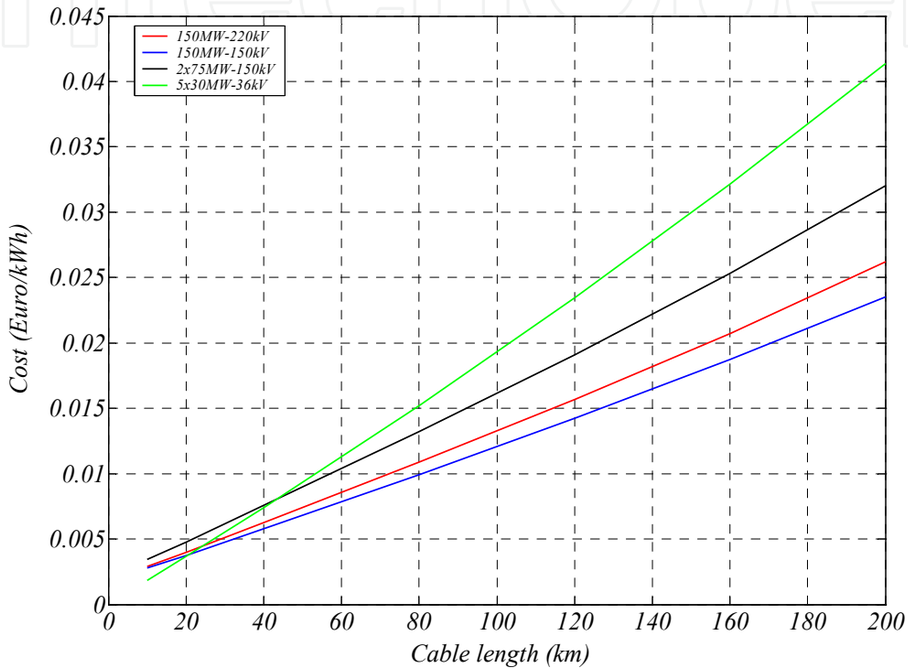


Figure 5.8 Energy transmission cost for different layouts.

In agreement with built wind farms, MVAC transmission systems are the best option near to shore. With short cable lengths (<20Km) MVAC connections are more economic than other layouts, due to the money saved in the offshore platform. On the contrary, with big cable lengths the cables costs do not compensate the money saved in the offshore platform, because submarine cables are very expensive.

The configuration of the two clusters of 75 MW connected with 150kV have the smaller active power losses, but it is not the cheapest option to transmit the energy to shore for any considered length in the considered conditions. The bigger transmitted energy due to the less conduction losses does not compensate the cost of an extra cable.

Considering the cost difference in reactive power compensators and the cable, the option of 150kV option is cheaper than the option of 220kV. What's more, for lengths bigger than 160 Km, the option of 220kV have more conduction losses, increasing the cost difference for long lengths.

Notice that these results are for a location with an average wind speed of 9 m/s and for the considered costs. A strong variation in considered cost estimations can change these results, i.e. these results are an approximation using these cost estimations.

5.2 Characterization of a base offshore wind farm

Based on the lay-out selection process of the previous section and the current state of the technology, in the present section the main components of a wind farm are characterized. The objective is the definition of a base scenario to perform based on it several analyses of the critical aspects in the offshore wind farms energy transmission and grid integration.

For that purpose, the physical characteristics of the offshore wind farm, as well as the model used for represent these components are defined. For active elements also their associated control strategy is described.

5.2.1 General layout of the considered offshore wind farm

Considering a 150 MW rated power offshore wind farm in a location 50km to the shore (cable length), a HVAC lay-out with a transmission voltage level of 150kV is the most cost effective option, based on the previous section 5.1.

Looking to the current state of wind turbines technology, modern turbines being erected both onshore and offshore are likely to be generating between 1.5 MW onshore and 3MW offshore [74]. More specifically, Vestas has a 3 MW wind turbine, the V90-3MW and Siemens Wind Power has two products, rated at 2.3MW and 3.6MW.

However, the situation is changing. REpower, has recently installed its first offshore turbines, rated at 5MW (soon to be increased to 6MW). Furthermore, Multibrid (Areva) is preparing to install its first turbines offshore, also rated at 5MW [75].

A progression from the G10X 4.5-MW turbine, Gamesa is developing the G11X, a permanent magnet generator with full-scale converter [76]. In the same way, Vestas, is developing the V112-3.0MW Offshore, which also has a permanent magnet generator with a full-scale converter [77]. As the other manufacturers, General electric has the GE 4.0-110 offshore turbine, a permanent magnet generator, with direct-drive technology [78].

In concordance with the plans of the manufacturers, several reports predicted that in the future, the rated power of the offshore wind turbines will be 5MW or bigger [24], [79]. Therefore, following the trend of the wind turbine manufacturers, the considered wind turbines for the base scenario have 5 MW rated power and full-scale converter, see section 2.5.3.4.

With regards to the spatial disposition of the wind turbines, it is considered as a rectangular (see section 3.3). The separation between wind turbines is varied depending on the size of the wind turbines (due to the aerodynamic efficiency) and to avoid overvoltage in each feeder, from 500m to 1000m [40]. In this case, this separation is considered 1000m.

The inter turbine grid, typically medium voltage, has a 33kV voltage (see section 3). The design of the inter-turbine grid is considered radial without any redundant connections. Due to the fact that the most of the offshore wind farms have not these connections [41]. For the considered scenario, each one of those radials is composed by 6 wind turbines of 5MW.

In short, the base scenario used to analyze the critical aspects of the energy transmission is shown in Figure 5.9.

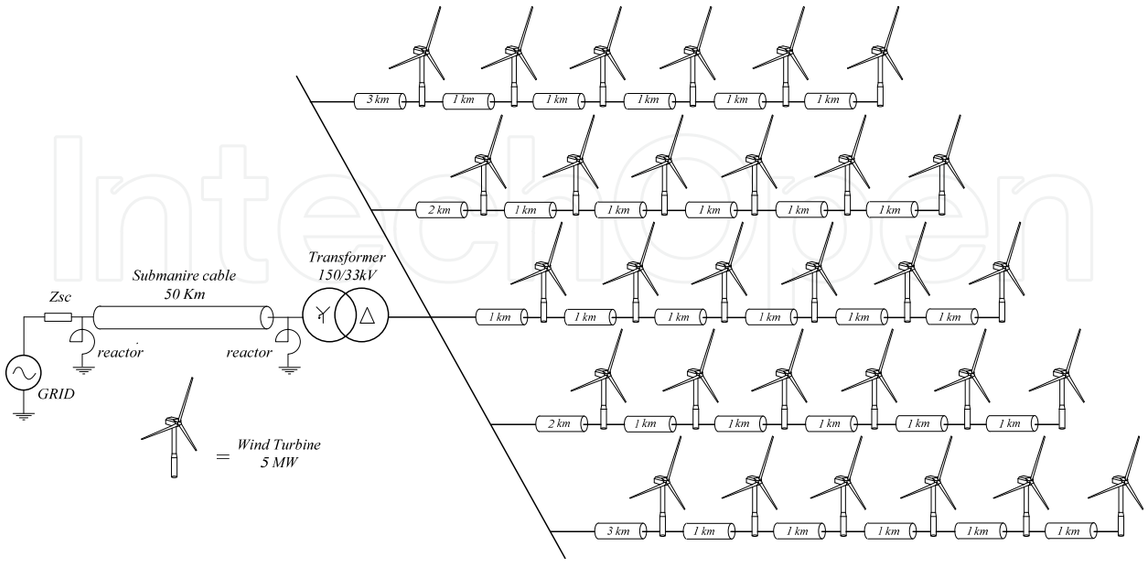


Figure 5.9 The lay-out of the base offshore wind farm, which is the base of the performed analysis.

General description of the main parts of the offshore wind farm:

1. **Wind farm:** Made up with 30 wind turbines of 5 MW.
2. **Inter-turbine grid:** Composed by five feeders of 30 MW (6 wind turbines) connected at 33kV voltage level. The spatial disposition of the grid has a square shape with a separation of 1km between wind turbines. There is not implemented any kind of redundant connections.
3. **The step-up transformer:** The step-up transformer increases the voltage of the inter turbine grid to a suitable voltage to the transmission system. Due to the fact that the inter-turbine grid has a 33kV service voltage and the energy transmission is performed at 150kV.
4. **Collector point:** The point where the energy generated in the wind farm is collected to transmit through the submarine cable to the PCC.
5. **Submarine cable**: The physical medium to transfer the energy from the PC (the collector point) to the PCC (Point of common coupling). This energy is carried at 150kV and through a 50 Km submarine cable.
6. **Reactive power compensation:** Huge reactors placed at both ends of the submarine cable, adjusted to the conditions where the cable is transmitting the rated power. The purpose of those reactors is the management of the reactive power through the cable and the improvement of the energy transmission. Reduces the required rated current of the cable and active power losses.
7. **Point of common coupling (PCC):** The point where the transmission system of the wind farm meets the main grid. The point where the transmission system has to fulfill the grid code requirements (THD, Power factor, LVRT…).
8. **Main grid**: The main distribution grid, in the present case simplified as a ideal voltage source and a sort circuit impedance.

5.2.2 Wind turbine

The manufacturer industry is developing the offshore wind turbines technology to bigger rated powers and to permanent magnet generators with direct drive. As a result, the main manufactures have wind turbines in this way: G10X 4.5-MW of Gamesa has a permanent magnet generator and full converter, like GE 4.0-110 of General Electric and The V112 of Vestas.

Thus, as the standard wind turbine for the base scenario is defined a 5MW, full-scale converter wind turbine with permanent magnet generator, Figure 5.10.

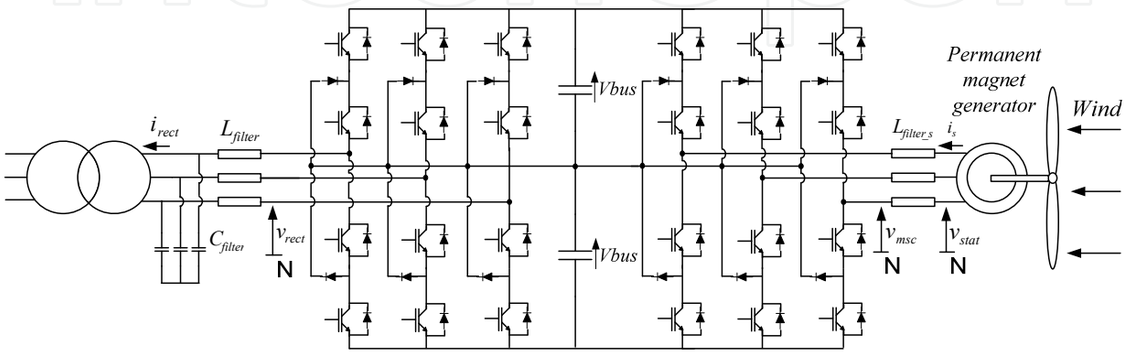


Figure 5.10 Electric scheme of the Neutral-point-clamped full-scale converter wind turbine based on a permanent magnet generator (direct drive).

For the technology of the converter, a neutral-point-clamped topology has been considered. Following the trend of increasing power and voltage levels in wind-power systems [39].

As the power ratings of the wind turbines increases, medium-voltage converters become more competitive. The cost of the cables and connections are reduced at this voltage level and those for the transformer and generator are barely affected. Furthermore, medium voltage converters need fewer components and as a result improve the reliability of them [80].

Therefore, considering this power range (5 MW) and the nature of the application (wind energy) a three-level topology is used with a 3.3kV (v_{rect}) output voltage. For the semiconductors, IEGTs (Injection Enhanced Gate Transistor) are used and an 1100 Hz switching frequency.

In short, some features very similar to the Ingedrieve MV 300 of Ingeteam (Figure 5.11), which is used as a reference to characterize the full-scale converter of the considered wind turbine.



(a) (b)

Figure 5.11 (a) External appearance of the Ingedrive MV 300 of Ingeteam and (b) The basic power module (BPM) equivalent to a branch of the three-level converter, the module is composed by 4 IGBTs, 4 weeling diodes and 2 clamp diodes, all of them based on IEGTs technology.

The general characteristics of the Ingedrive MV 300 of Ingeteam [81] are summarized in Table 7.8.

Characteristic	***Value***
Rated Output Power:	*8 MVA*
Topology:	*NPC 3 Level AFE (press pack IEGTs)*
Cooling System:	*Deionized Water Cooled*
Line Supply Voltage:	*3300 Vac ±10%*
Line Supply Frequency:	*50 / 60 Hz ± 5%*
Rated Output Current:	*1475 Aac*
Efficiency at 100% of the Rated Operating Point:	*97.8 %*
PWM Frequency	*1 kHz*

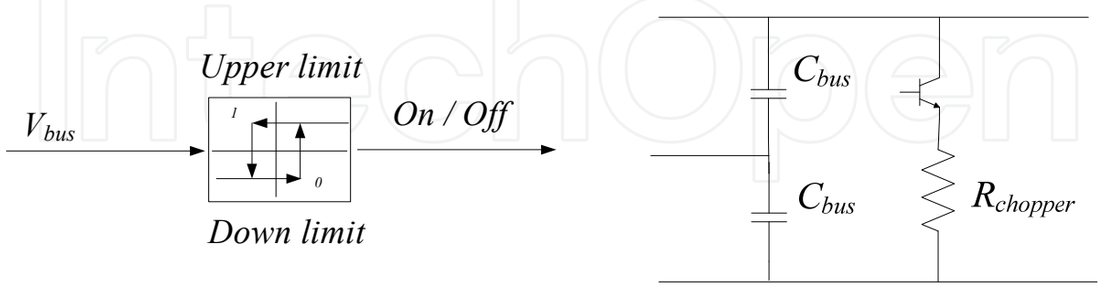
Table 5.8 General characteristics of the ingedrive MV 300 of Ingeteam.

The machine side converter not always can reduce the collected active power or cannot do that reduction as fast as is required. In these cases, the difference between the active power collected by the machine side converter and the evacuated active power by the grid side converter will lead to increase the DC voltage of the BUS.

To solve this problem, i.e. to avoid over voltages in the BUS, the wind turbine is provided with a chopper circuit to consume this exceeded energy.

The DC-link brake chopper allows the wind turbine to keep connected during the grid faults by wasting the active power impossible to evacuate to the grid. As a result, avoids over voltages in the DC-link during the grid faults [82], [83].

In the present case, the control strategy of the DC chopper is On/Off kind, Figure 5.12 (a). Activating and deactivating the DC chopper, in order to maintain the DC-link voltage in a suitable range. In short, if the voltage in the DC-link trespasses the upper limit, the DC chopper is activated to reduce the voltage of the DC-link, on the contrary, when the voltage in the DC-link trespasses the down limit the DC chopper is disconnected.



(a) (b)

Figure 5.12 (a) Control block diagram (On/Off) of the DC chopper. (b) Electric lay-out of the considered chopper circuit.

5.2.2.1 Considered wind turbine model

To model the considered wind turbines some simplifications are performed. Firstly, the grid side and the generator side converters are considered decoupled. Thus, as the analysis is focused on the electrical aspects of the offshore wind farms power transmission, only the grid side converter is considered [39], [84]. The generator-side converter and their respective controllers are not included in the model [85], [88].

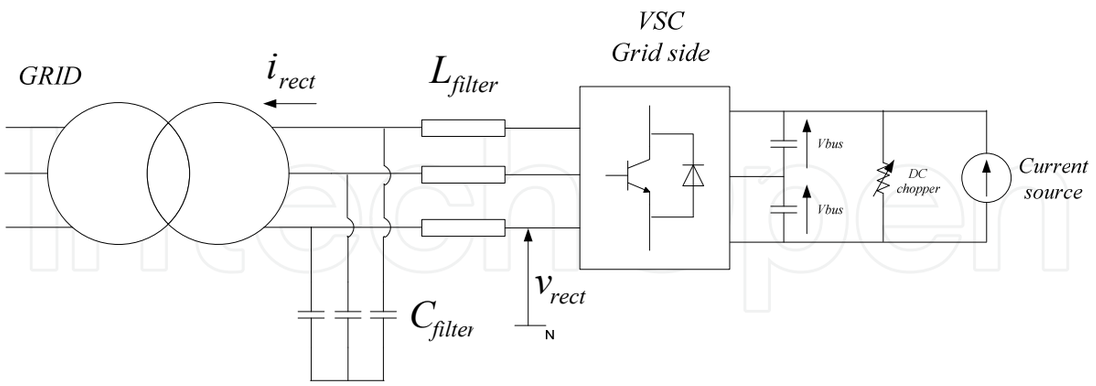


Figure 5.13 Electric scheme of the considered wind turbine model.

5.2.2.2 Control strategy of the grid side converter

The wind turbine has its own grid code requirements. These requirements are over the same aspects of the wind farms requirements (THD, LVRT…) and oriented to help the wind farm

accomplishing grid codes. One of the most demanding requisite that has to afford a wind turbine is the LVRT requirement [89] (see section 5.2.2.4).

In this way, most voltage dips caused by network faults can be decomposed in positive-negative and zero-sequence components. Thus, it is reasonable to use these symmetrical components in the control of the grid side voltage converter (VSC) [90], [91].

Under a unbalanced voltage dip situation, the active and reactive power exchanged by the converter with the grid, present an oscillatory behavior that can be represented according to the following expressions [92]:

$$P(t) = P_0 + P_{c2} \cdot \cos(2wt) + P_{s2} \cdot \sin(2wt) \tag{118}$$

$$Q(t) = Q_0 + Q_{c2} \cdot \cos(2wt) + Q_{s2} \cdot \sin(2wt) \tag{119}$$

Where, each term of these equations can be represented in the *dq* frame (see appendix D) as:

$$P_0 = \frac{3}{2}\left(v_d^{+} i_d^{+} + v_q^{+} i_q^{+} + v_d^{-} i_d^{-} + v_q^{-} i_q^{-}\right) \tag{120}$$

$$P_{c2} = \frac{3}{2}\left(v_d^{+} i_d^{-} + v_q^{+} i_q^{-} + v_d^{-} i_d^{+} + v_q^{-} i_q^{+}\right) \tag{121}$$

$$P_{s2} = \frac{3}{2}\left(v_q^{-} i_d^{+} + v_d^{-} i_q^{+} + v_q^{+} i_d^{-} + v_d^{+} i_q^{-}\right) \tag{122}$$

$$Q_0 = \frac{3}{2}\left(v_q^{+} i_d^{+} + v_d^{+} i_q^{+} + v_q^{-} i_d^{-} + v_d^{-} i_q^{-}\right) \tag{123}$$

$$Q_{c2} = \frac{3}{2}\left(v_q^{+} i_d^{-} + v_d^{+} i_q^{-} + v_q^{-} i_d^{+} + v_d^{-} i_q^{+}\right) \tag{124}$$

$$P_{s2} = \frac{3}{2}\left(v_d^{+} i_d^{-} + v_q^{+} i_q^{-} + v_d^{-} i_d^{+} + v_q^{-} i_q^{+}\right) \tag{125}$$

Focusing the previous set of equations to the positive sequence, the *dq* positive current references can be calculated as:

$$\begin{bmatrix} i_d^{+*} \\ i_q^{+*} \\ i_d^{-*} \\ i_q^{-*} \end{bmatrix} = \frac{3}{2} \cdot \begin{bmatrix} v_d^{+} & v_q^{+} & v_d^{-} & v_q^{-} \\ v_d^{-} & v_q^{-} & v_d^{+} & v_q^{+} \\ v_q^{+} & -v_d^{+} & v_q^{-} & -v_d^{-} \\ v_q^{-} & -v_d^{-} & v_q^{+} & -v_d^{+} \end{bmatrix}^{-1} \cdot \begin{bmatrix} P_0^{*} \\ 0 \\ Q_0^{*} \\ 0 \end{bmatrix} \tag{126}$$

Therefore, based on the reactive power reference (Q_0*) and the active power reference (P_0*, imposed by the DC bus voltage regulator), the references for the positive sequences of the currents are calculated by using the inverse matrix (A^{-1}), equation (126).

As regards to the negative current references, the objective of the converter is to compensate as much as possible the negative sequence components. Consequently, the references for the negative sequences of the currents are always zero.

The current controllers are implemented using two proportional-integral gains in the *dq* frame with cross-coupled terms ($V_{d_cct}^{-}$, $V_{d_cct}^{+}$, $V_{q_cct}^{-}$ and $V_{q_cct}^{+}$) for each sequence (positive and negative). To estimate these cross-coupled terms, the LC-L filter is simplified considering it as a L filter [93]. The block diagram of the control strategy is depicted in Figure 5.14.

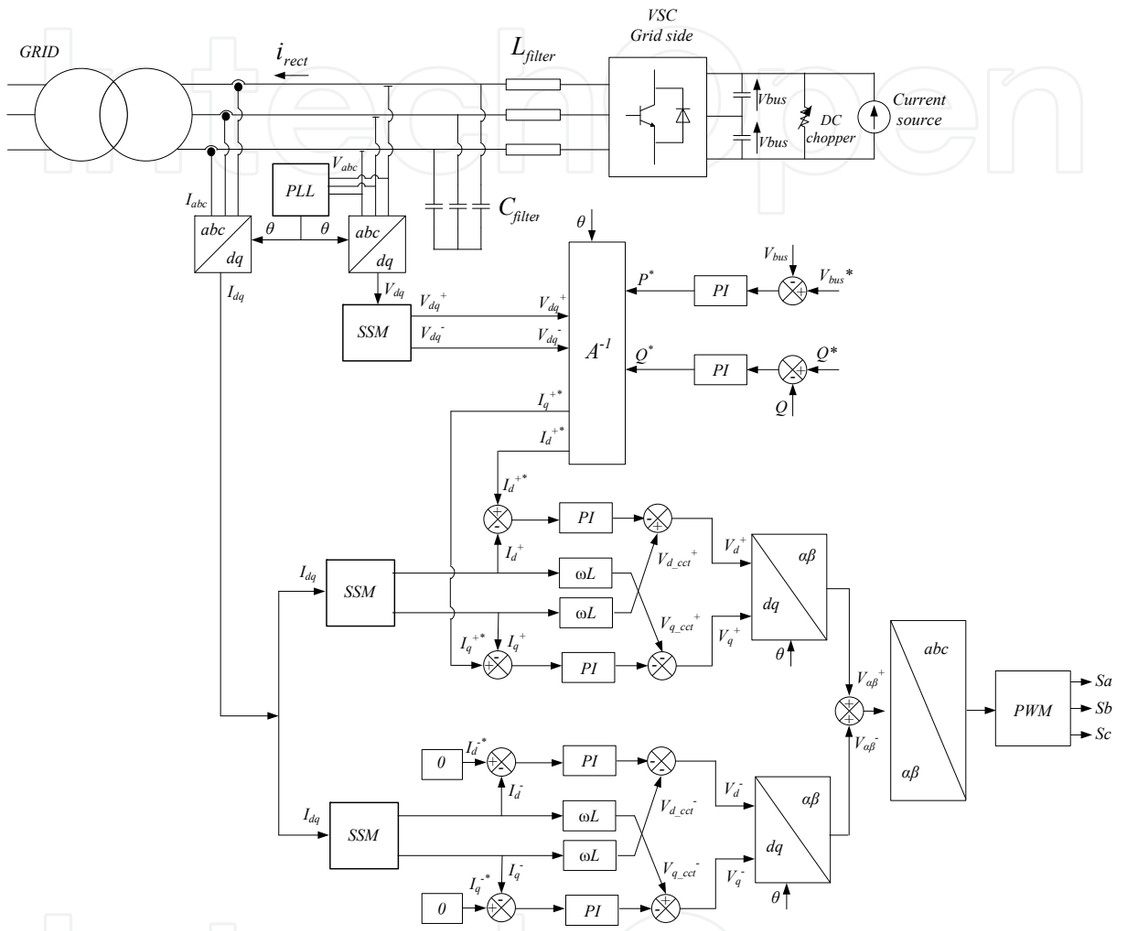


Figure 5.14 The block diagram of the implemented control strategy.

The control strategy is based on positive and negative sequences. Consequently a sequence separation method (SSM) is used to extract the sequences.

As grid side converter, it has to be synchronized with the phase angle of the grid. To achieve this synchronization, a phase locked loop (PLL) working with an SSM is used. In this way, the PLL can guarantee angle precision when asymmetrical grid faults or unbalanced grid conditions occurs [39], [94].

For the implementation of the PLL, the "*d*"-axis of the synchronous reference frame is aligned with the positive sequence vector of the grid voltage.

5.2.2.3 Grid side converter's connection filter

To choose an optimal filter topology for the NPC inverter of the offshore wind turbines, the efficiency, weight and volume have to be considered. Due to the fact that in comparison with other application, offshore are difficulties with the transportation and the installation of the filters.

In this way, LCL filters have the advantage of providing a better decoupling between filter and grid impedance (reducing the dependence on grid parameters). In this kind of filters it is also possible the reduction of the cost and weight by increasing the value of the capacitor [95].

Thus, to connect the grid side inverter to the inter-turbine grid a LCL filter is used [95], [96]. The filter of the base offshore wind farm is adjusted with the following criteria:

- The resonant frequency of the filter has to be less than the half of the switching frequency.
- The resonant frequency of the filter has to be at least 10 times bigger than the fundamental frequency.

The characteristics of the considered LC-L filter are summarized in Table 7.9 and the frequency response is shown in Figure 5.15.

LCL values	*Fres*
0.8 mH-175uF-0.4mH	*550Hz*

Table 5.9 Characteristics of the LCL filter.

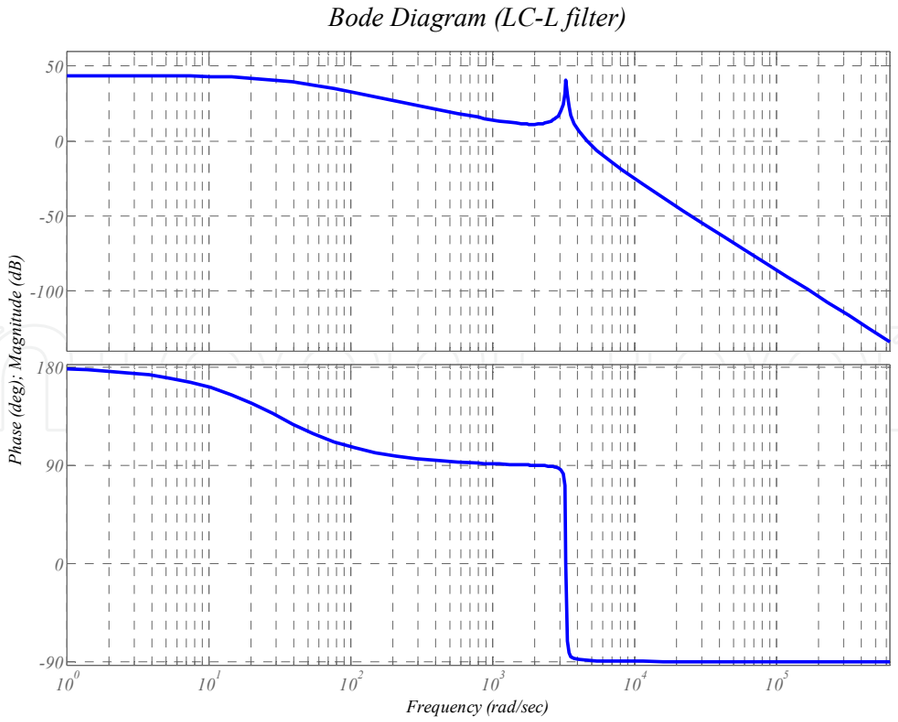


Figure 5.15 Bode diagram of the LC-L filter.

5.2.2.4 Verification that the wind turbine is suitable to connect to the main grid according to the grid code requirements

All the offshore wind farms connected to a transmission grid have to fulfill with the grid code requirements of the system operator (SO). In the present studio, the considered offshore wind farm is connected to a distribution grid operated by REE. So, the offshore wind farm and the wind turbines placed in it have to fulfill the REE grid code requirements (P.O. 12.3).

In this way, for a specific grid code requirements, it is possible to homologate the control strategy and the considered features of the wind turbines. Because, if the proposed wind turbine model fulfills the REE grid code requirements and this fulfillment is verified by using the standard procedure, this model can be considered as a realistic approximation.

Looking into the grid code requirements, the most demanding requisite for wind farms and wind turbines is the Low Voltage Ride Through capability [97], [98] and [99]. Therefore, in the present section this aspect is analyzed to validate the wind turbine model.

5.2.2.4.1 Verification procedure established by REE

For testing and validation wind turbines, i.e. to make sure that the wind turbines fulfill the grid code requirements. REE have defined a procedure detailing all the tests and characteristics in the validation process, the PVVC (Procedimiento de verificación, validación y certificación de los requisitos del PO 12.3 sobre la respuesta de las instalaciones eólicas ante huecos de tensión) [101].

Requirements of the PVVC to validate a wind turbine model

The PVVC specifies in its section 6.2.2 (test conditions for the direct fulfillment of the P.O. 12.3, Particular process) the conditions for each fault category (Table 5.12) for the direct fulfillment of the P.O. 12.3. The PVVC specifies the validation criteria as follows:

- The reactive power consumption of the wind turbine in the zone A of the fault (see Figure 5.16) will not exceed the 15% of its rated power, in 20 ms cycles. On the contrary, in the zone B of the fault, this consumption will not exceed the 5% of its rated power, in 20 ms cycles.

- The net reactive current consumption of the wind turbine after the fault clearance in the zone delimited by T_3 and T_3+150ms, in 20 ms cycles, must not exceed 1.5 times the rated current, even if the voltage is above the 0.85 pu.

Procedure to define voltage dips or faults:

Based on the IEC 61400-21 standard, the PVVC defines the way to measure the depth of a grid fault, as well as is defined the method to produce the fault. In this way, PVVC specifies that the voltage dip has to be independent to the tested wind turbine. Therefore, the voltage dip is measured in a "no-load" scenario, with the wind turbine disconnected.

According to the PVVC, the voltage dips must be generated using a voltage divider. This divider consists of two inductances in series: The short circuit inductance with a "shock" inductance and a fault or dip inductance, as can be seen in Figure 5.17.

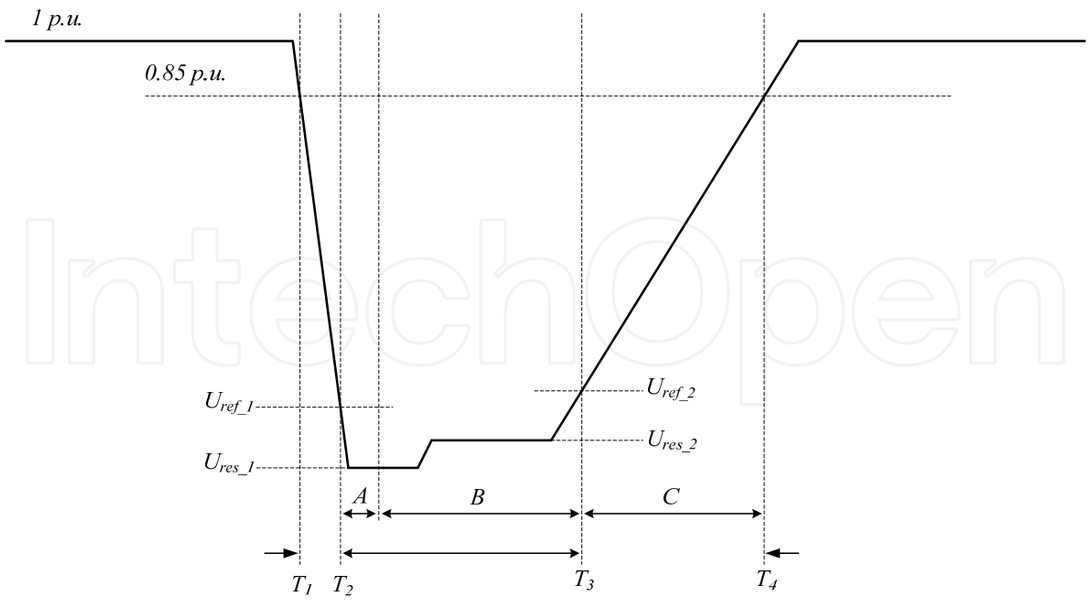


Figure 5.16 Voltage dip characterization and definition in zones.

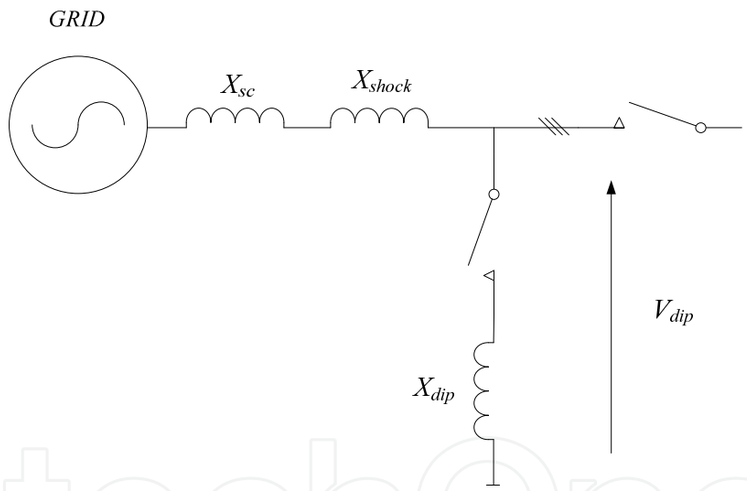


Figure 5.17 Defined test scheme in the PVVC to measure the depth of the voltage fault.

For different dip types, the value of the residuary voltage and the duration are defined in the PVVC as is summarized in Table 5.10

Dip type	**Residuary voltage of the fault** *(Ures)*	**Voltage tolerance** *(UTOL)*	**Dip time** *(ms)*	**Time tolerance** *(TTOL, ms)*
Three phase / One phase	≤(20%+UTOL)	+3%	≥(500-TTOL)	50
Two phase ungrounded	≤(60%+ UTOL)	+10%	≥(500-TTOL)	50

Table 5.10 Dip voltage characteristics for the test with the wind turbine disconnected.

The value of the residuary voltage is calculated via equation (127):

$$V_{dip}(p.u.) = V_{grid}(p.u.) \cdot \frac{X_{dip}(p.u.)}{X_{dip}(p.u.) + X_{shock}(p.u.) + X_{sc}(p.u.)} \tag{127}$$

Diagram of the simulation scenario

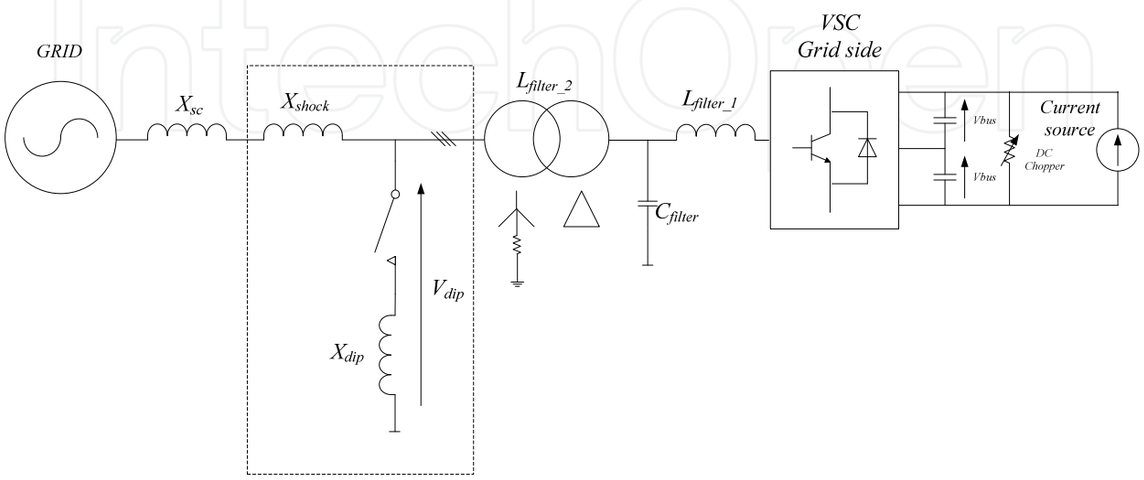


Figure 5.18 Defined test circuit in the PVVC to measure the LVRT capabilities of the wind turbine.

Parameter	*Value*
L_{filter_1}	*11,63%*
L_{filter_2}	*12%*
X_{dip}	*Depending on the depth of the fault*
$X_{shock} + X_{sc}$	*5%*

Table 5.11 Value of the impedances of the simulation scenario.

X_{shock} and X_{sc} impedances have the objective to limit the short circuit current of the grid during faults. As a result, the value of these impedances has specified boundaries in the standard procedure. According to the PVVC, the sum of the both impedances is limited to allow a grids short circuit power equal or bigger than five times the registered rated power of the wind farm (<20%). In the present simulation scenario is chosen 5%.

Considered tests to validate the wind turbine model:

To test and validate the wind turbines, four tests are defined in the PVVC, illustrated in Table 5.12

Category	*Operating Point*	*Dip type*
1	*Partial Load*	*3 phase*
2	*Full Load*	*3 phase*
3	*Partial Load*	*2 phase*
4	*Full Load*	*2 phase*

Table 5.12 Faults and characteristics taken into account in the PVVC.

To be more specific, the PVVC has limited the terms "partial load" and "full load" in a specific operation range, Table 5.13. In the present analysis, there is considered 20% for partial load and 90% for full load.

	Registered active power	*Power factor*
Partial Load	*10%-30% Pn*	*0,90 inductive -0.95 capacitive*
Full Load	*>80% Pn*	*0,90 inductive -0.95 capacitive*

Table 5.13 Definition of the operation point ranges before faults.

5.2.2.4.2 Results of the considered wind turbine upon the verification procedure

Results of a fault category 1: Three-phase fault - partial load

	Limit P.O. 12.3	**Test results**
Net reactive power consumption, in cycles of 20ms, during a period of 150ms after the beginning of the fault:	-0.1500	0
Net reactive power consumption, during a period of 150ms after the clearance of the fault:	-0.0900	0
Net reactive current consumption, in cycles of 20ms, during a period of 150ms after the clearance of the fault:	-1.5000	-0.2584
Net active power consumption during the fault:	-0.1000	-0.0256
Net reactive power consumption during the fault:	-0.0500	0
Fulfillment of the $I_{reactive}$ / I_{total} requirement:	0.9000	0.9981

Table 5.14 Summarized results of a 1st category fault for the test defined in the PVVC.

Results of a fault category 2: Three-phase fault - full load.

	Limit P.O. 12.3	**Test results**
Net reactive power consumption, in cycles of 20ms, during a period of 150ms after the beginning of the fault:	-0.1500	-0.0467
Net reactive power consumption, during a period of 150ms after the clearance of the fault:	-0.0900	0
Net reactive current consumption, in cycles of 20ms, during a period of 150ms after the clearance of the fault:	-1.5000	-0.2874
Net active power consumption during the fault:	-0.1000	-0.0266
Net reactive power consumption during the fault:	-0.0500	0
Fulfillment of the $I_{reactive}$ / I_{total} requirement:	0.9000	0.9980

Table 5.15 Summarized results of a 2nd category fault for the test defined in the PVVC.

Graphic results:

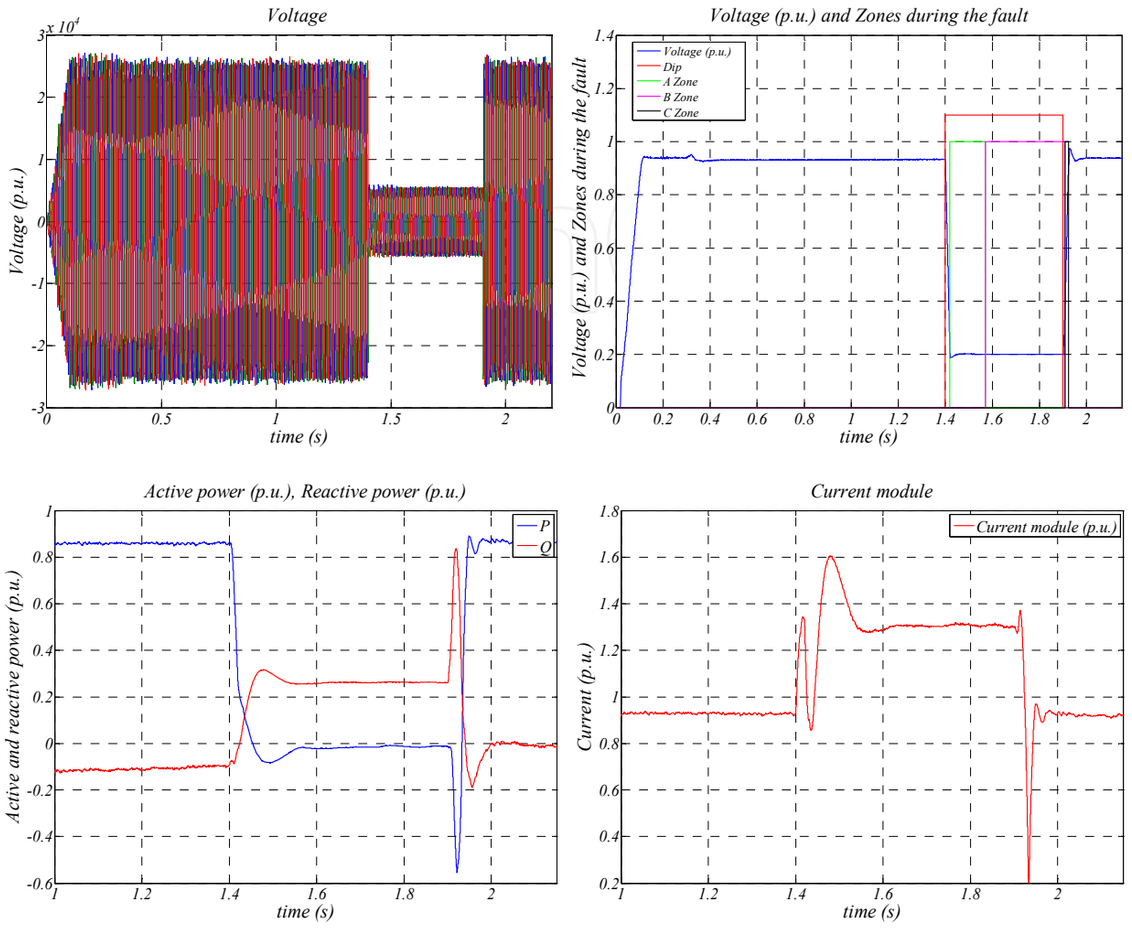
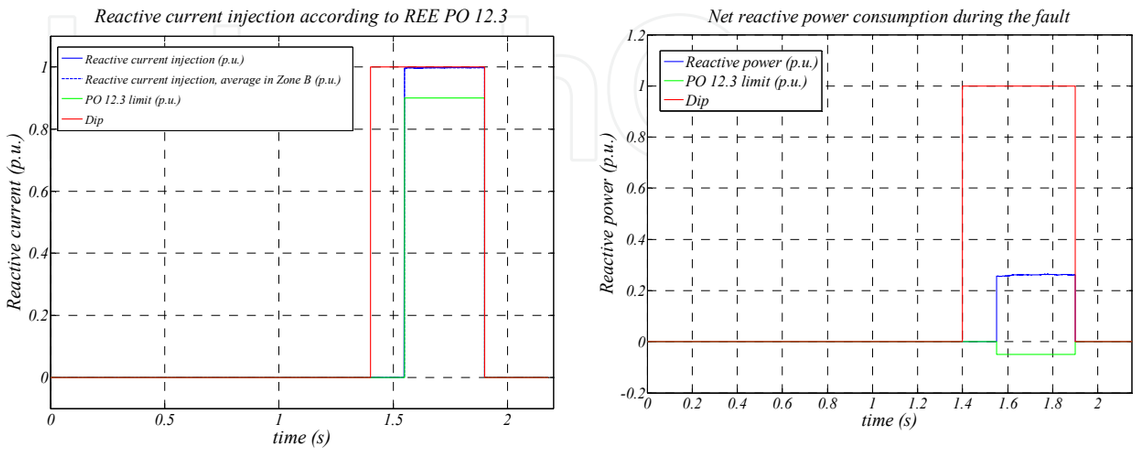


Figure 5.19 Summarized graphical results of a 2nd category fault for the test defined in the PVVC, voltage (module and signals), power and current results.



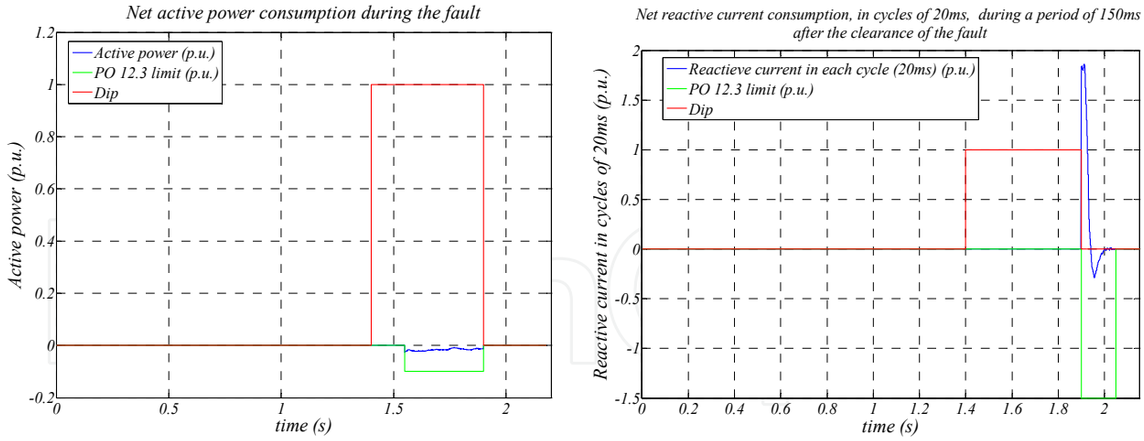


Figure 5.20 Summarized graphical results of a 2nd category fault for the test defined in the PVVC, reactive current and power consumption in B zone and reactive current consumption in C zone.

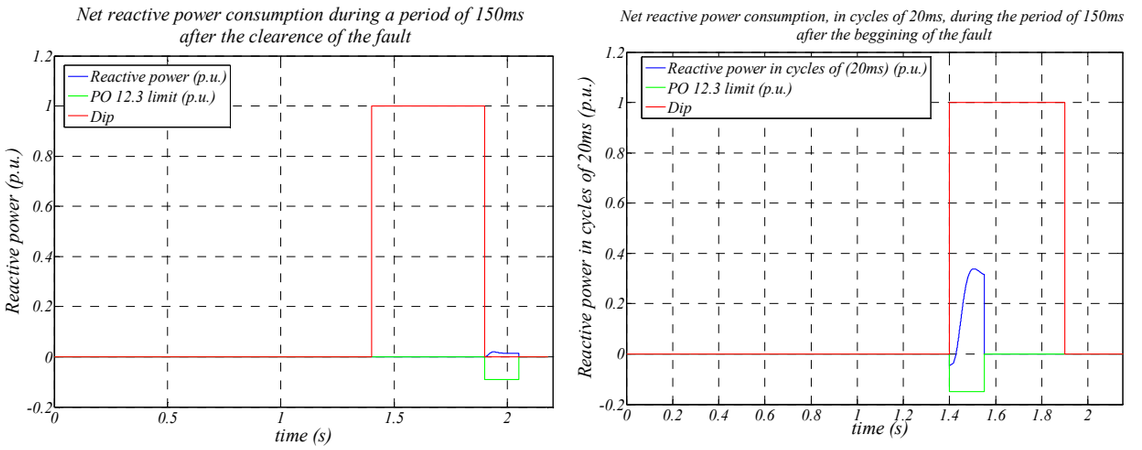


Figure 5.21 Summarized graphical results of a 2nd category fault for the test defined in the PVVC, reactive power consumption in C zone and A zone.

Results of a fault category 3: Two phase ungrounded fault - partial load

	Limit P.O. 12.3	**Test results**
Net reactive power consumption, in cycles of 20ms, during the maintenance of the fault:	-0.4000	0
Net reactive power consumption, during the maintenance of the fault:	-0.0400	0
Net active power consumption, in cycles of 20ms, during the maintenance of the fault:	-0.3000	0
Net active power consumption, during the maintenance of the fault:	-0.0450	0

Table 5.16 Summarized results of a 3rd category fault for the test defined in the PVVC.

Results of a fault category 4: Two phase ungrounded fault - full load

	Limit P.O. 12.3	**Test results**
Net reactive power consumption, in cycles of 20ms, during the maintenance of the fault:	-0.4000	0
Net reactive power consumption, during the maintenance of the fault:	-0.0400	0
Net active power consumption, in cycles of 20ms, during the maintenance of the fault:	-0.3000	0
Net active power consumption, during the maintenance of the fault:	-0.0450	0

Table 5.17 Summarized results of a 4th category fault for the test defined in the PVVC.

Graphic results:

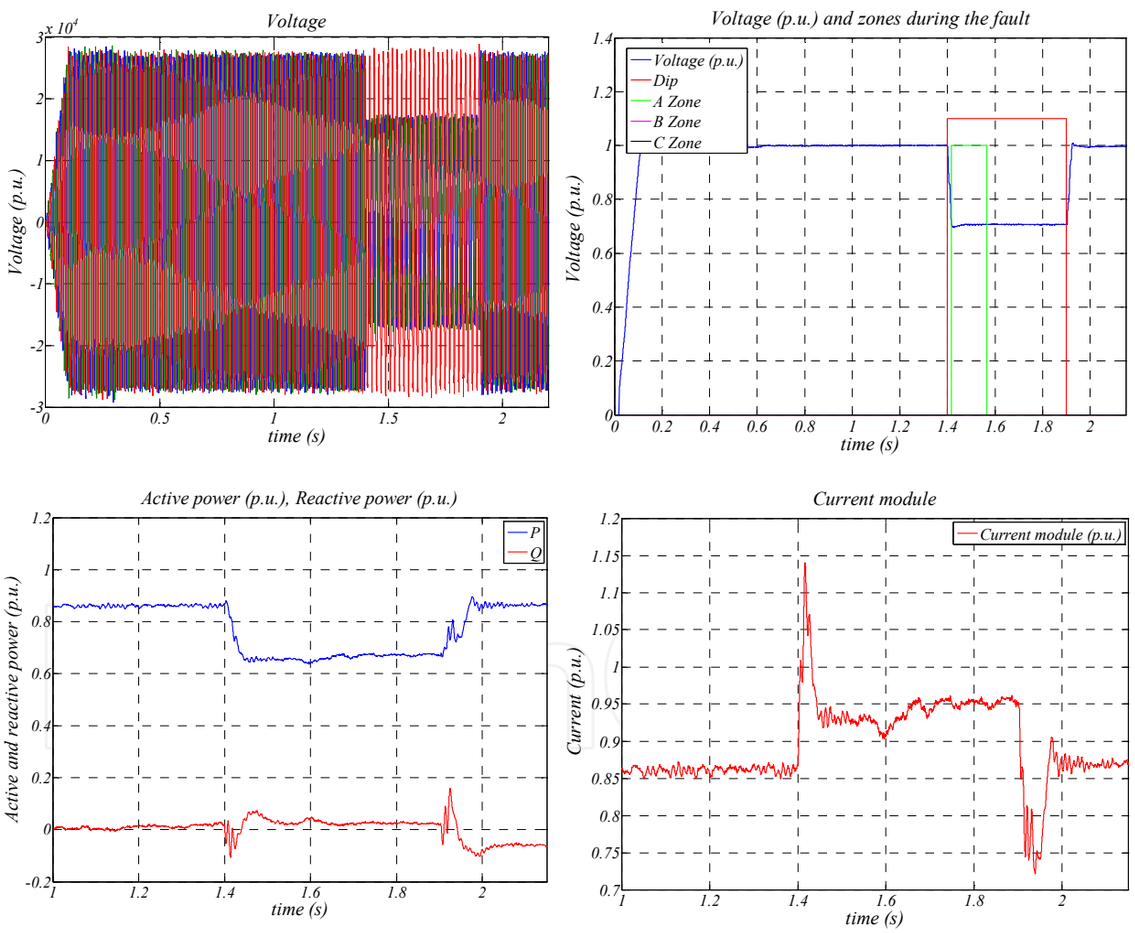


Figure 5.22 Summarized graphical results of a 4th category fault for the test defined in the PVVC, voltage (module and signals), power and current results.

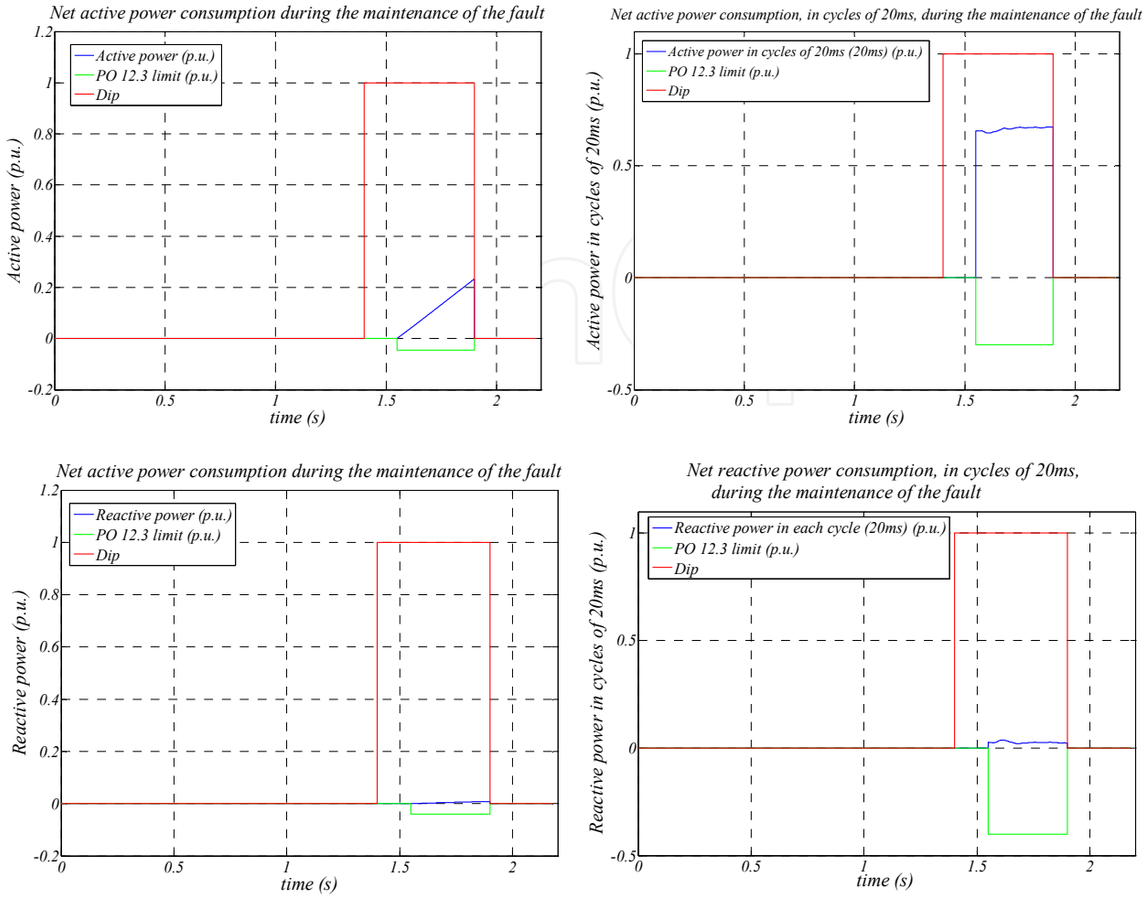


Figure 5.23 Summarized graphical results of a 4th category fault for the test defined in the PVVC, active and reactive power consumption in B zone.

5.2.3 Step-up transformer of the wind turbines and the offshore platform

The transformer is modeled as the "classic model" [102], [103]. The electric equivalent diagram is depicted in Figure 5.24

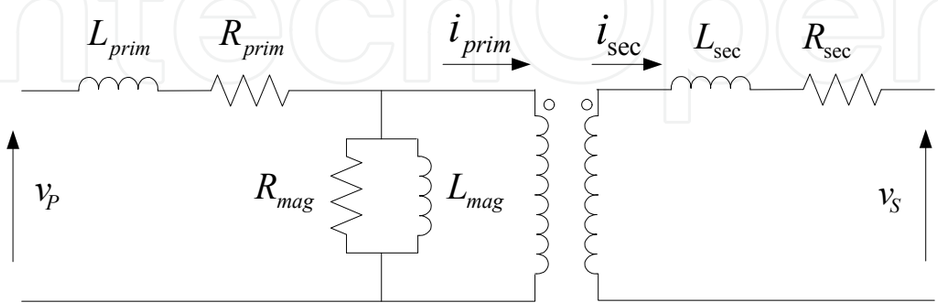


Figure 5.24 Electric equivalent diagram per phase of the transformer model.

The step-up transformer of the base offshore substation has the following characteristics described in Table 5.18

Parameter	*Value*
Rated power	150 MVA
Primary voltage	33 kV
Secondary voltage	150 kV
Connection	Δ- gY
Transformers leakage resistance	1 %
Transformers leakage inductance	6 %
No load losses	1,78 %

Table 5.18 Characteristics of the step-up transformer in the offshore substation.

In the same way, the step-up transformer of the wind turbine has the characteristics summarized in Table 5.19

Parameter	*Value*
Rated power	5 MVA
Primary voltage	3,3 kV
Secondary voltage	33 kV
Connection	Δ- gY
Transformers leakage resistance	1 %
Transformers leakage inductance	6 %
No load losses	1,78 %

Table 5.19 Characteristics of the step-up transformer in the wind turbine.

5.2.4 AC submarine cables

The model and the features of the submarine cables are widely explained in chapter 4. So, in the present section only a resume of the considered submarine cable characteristics is carried out.

The length of the transmission submarine cable for the base scenario is 50 Km and it is modeled using the frequency dependent model in phase domain (section 4.2.2.3.2). The physic characteristics of the transmission cable provided by the manufacturer (Courtesy by General Cable) are shown In Table 5.20.

The other submarine cable used in the base scenario is the medium voltage inter-turbine cable. This cable has to be suitable to connect 6 wind turbines (30MW) of the feeder at 33kV voltage level to the collector point, i.e. suitable to carry at least 525 A.

Therefore, as the inter-turbine submarine cable, an ABB XLPE cable [45] with the adequate nominal voltage and power is chosen. The characteristics of this cable are shown in Table 5.21. This submarine cable is also modeled with the frequency dependent model in phase domain (section 4.2.2.3.2).

Parameter	*Value*
Rated voltage	87 / 150kV
Rated current	1088 A
Conductors cross section:	1.200 mm²
Separation between conductors:	97.839996 mm
Buried depth	1 m
Shields cross section	30 mm²
Shield type:	Metallic strip
Armor type:	Strands crown
Diameter of conductor	43,5 mm
Insulation thickness	20 mm
Diameter upon the insulation	88,5 mm
Diameters down the sheath:	215,6 mm
Diameter down the armor:	226,7 mm
Sheath thickness:	8,9 mm
External diameter:	244,5 mm
Relative dielectric constant:	2,50
Resistivity of the conductor d.c. at 20°C:	0,0151 Ohm/km
Resistivity of the conductor a.c.	0,0205 Ohm/km
Resistivity of the shield d.c. at 20°C:	0,6264 Ohm/km
Nominal capacitance of the cable:	0,233 μF/km
Inductance of the cable:	0,352 mH/km

Table 5.20 Cable characteristics provided by General Cable.

Parameter	*Value*
Nominal voltage	30kV (36kV)
Nominal current	765 (65ºC) – 930 (90ºC) A
Cross section of conductor	800 mm²
Separation between conductors	123.65 mm
Buried depth	1 m
Shields cross section	35 mm²
Diameter of conductor	33.7 mm
Insulation thickness	8 mm
Diameter upon the insulation	51.9 mm
Relative dielectric constant:	2,30
Resistivity of the conductor d.c. at 20°C:	0,02265 Ohm/km
Resistivity of the conductor a.c.	0,024959 Ohm/km
Nominal capacitance of the cable	0,38 μF/km
Nominal inductivity of the cable:	0,31 mH/km

Table 5.21 Characteristics of the inter-turbine submarine cable **[45]**.

5.2.5 The main grid

The main grid is modeled as ideal voltage source and a impedance [39], [83], [84] and [85]. The value of the impedance is calculated considering the point of common coupling (PCC) a strong point [86], [87], with a short circuit power 20 times bigger than the wind farms rated power (X_{sc}=5%). Consequently, the short circuit impedance is calculated by equations (128)-(130):

$$S_{sc} = 20 \cdot S_{windfarm} \tag{128}$$

$$S_{sc} = 3 \cdot V_{phase} \cdot I_{sc} = 3 \cdot X_{sc} \cdot I^2{}_{sc} \tag{129}$$

$$X_{sc} = \frac{S_{sc}}{3 \cdot I^2{}_{sc}} \tag{130}$$

Where: S_{sc} is the short circuit power of the PCC, $S_{windfarm}$ is the rated power of the wind farm, I_{sc} is the short circuit current and X_{sc} is the short circuit impedance. The short circuit impedance is considered an inductor as a simplification.

5.2.6 Protection scheme (Fuses and breakers)

As any other electrical installation, offshore wind farms must be protected against different eventualities in the system. Therefore, in this section, the breakers and fuses considered for the electrical connection infrastructure are defined.

In this way, the considered scenario has fuses in each wind turbine before the step up transformer (*Fuse WT*), see Figure 5.25.

With regards to the breakers, as for the fuses, it is considered one for each wind turbine (*BRK WT*), but in this case, the breakers are placed after the step-up transformer. Furthermore, there are considered auxiliary breakers to allow the disconnection of feeder parts (*BRK aux*) and breakers to disconnect complete feeders (*BRK 3 to BRK 7*).

Finally, in order to provide the offshore wind farm with the capability to disconnect completely from the grid, two general breakers are considered (*BRK 1* and *BRK 2*).

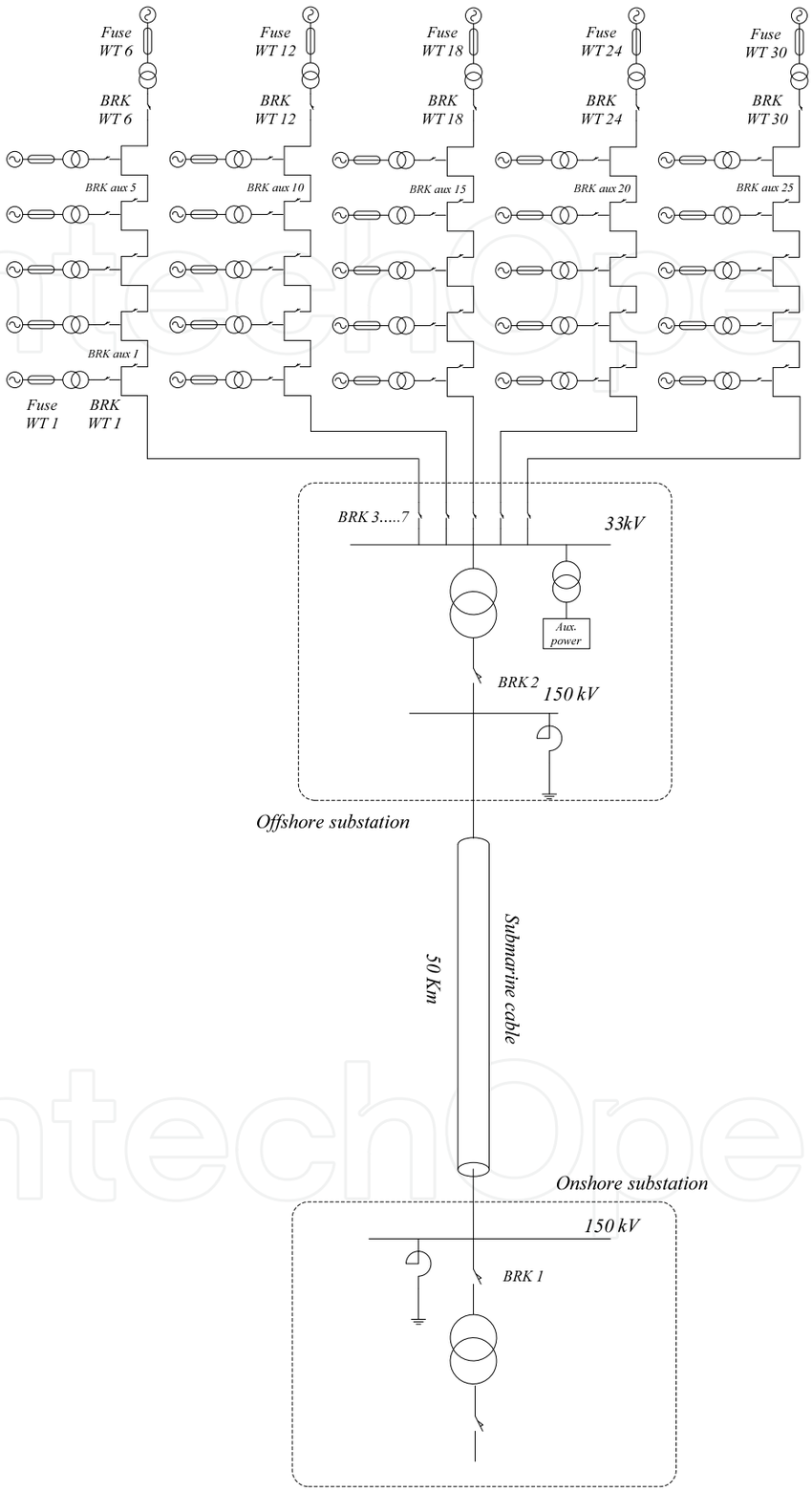


Figure 5.25 Complete electrical scheme of the considered offshore wind farm.

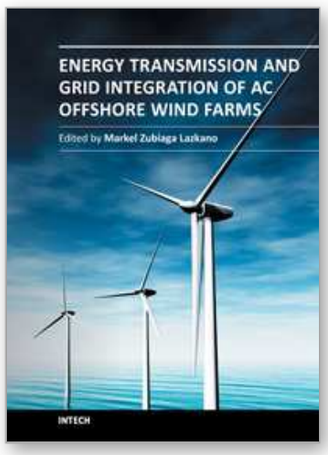
5.3 Chapter conclusions

The main objective of this book is the definition of a methodology to design AC offshore wind farms. To focus the problem, in the present chapter, the main elements of the base offshore wind farm are characterized based on the current state of the technology.

The wind turbines are considered a key issue for further analysis. So, after the definition of their rated power, the control strategy and the filter of the grid side converter, the wind turbines are tested via simulation to verify that they can fulfill the grid code requirements and as a result are suitable to place in the offshore wind farm.

Thus, considering this base scenario as a representative case, in the next chapters the key issues of the electric connection infrastructure are evaluated, such as: the frequency response for the electric connection infrastructure or the transient behavior of the offshore wind farm.

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This book analyses the key issues of the offshore wind farm's energy transmission and grid integration infrastructure. But, for this purpose, there are not evaluated all the electric configurations. In the present book is deeply evaluated a representative case. This representative case is built starting from three generic characteristics of an offshore wind farm: the rated power, the distance to shore and the average wind speed of the location. Thus, after a brief description of concepts related to wind power and several subsea cable modeling options, an offshore wind farm is modeled and its parameters defined to use as a base case. Upon this base case, several analyses of the key aspects of the connection infrastructure are performed. The first aspect to analyze is the management of the reactive power flowing through the submarine cable. Then, the undesired harmonic amplifications in the offshore wind farms due to the resonances and after this, transient over-voltage problems in the electric infrastructure are characterized. Finally, an offshore wind farm connection infrastructure is proposed in order to achieve the grid code requirements for a specific system operator, but not as a close solution, as a result of a methodology based on analyses and simulations to define the most suitable layout depending on the size and location of each offshore wind farm.

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