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Fault analysis and protection Design for Offshore wind farm Electrical System

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Abstract

This Master Thesis investigates the fault analysis for different types of faults events through the offshore wind farm electrical system including the onshore, offshore and the transmission HVDC line. An offshore wind farm electrical system is suggested and different study cases are executed.
A detailed discussion of the system behavior during the fault period is presented and the reflected effects on the faulted and the healthy part of the electrical system for the offshore wind farm are identified.
The study is conducted in DigSilent PowerFactory software, using elements templates from the global library and the application examples in the software.
Illustrating single line diagrams and plots for the fault current/voltages on the fault location and the other main elements are analyzed and discussed throughout the project cases.
The control concept for the onshore and offshore converters controllers are explained and the consequences on the protection system are discussed.

Hisham Hasan Taleb

PREFACE

This Master Thises has been accomplished at Aalborg Universities Department of Energy Technology, in Esbjerg, in the winter 2018 and spring 2019 by Hisham has Taleb group number OES10 / Group3
The project idea and proposal has been created by the discussion and agreement with the supervisor Amin Hajizadeh with a title of Fault Analysis and Protection Design for Wind Farm Electrical System.

The project concerns a different type of faults study cases executed in the offshore wind farm electrical system by utilizing a DigSilent PowerFacory software.
The literature references in the thesis are shown in IEEE style. References are marked with a single number in square brackets [1], Books in the bibliography is shown with; author, title, publisher, year of publication and ISBN number.

In this master thesis, the materials used have been obtained throughout researches, reports, articles, books, websites supported by advice and recommendations from the supervisor.

Acknowledgment
The author would like to indicate his thanks and appreciation for Amin Hajizadeh for his supervision and guidance throughout the project. Thanks also to Navid Bayati for his support within the DigSilenet PowerFactory software.

The following software is used within the project:

- *DigSilent* PowerFactory Software
- Microsoft Word
- Microsoft Visio

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Chapter 1

1. Introduction

As one of the most promising alternative sources for electrical power, the wind energy started to attract the attention of the researchers and companies besides the countries which have future energy challenges for its potential future developments.
The wind energy constructs a major part of the renewable energy, the environmentally friendly energy solution for the dilemma of the prospected shortage in the traditional production resources and the goal of CO2 emission reduction (The aim of Carbon – neutral energy).
The answer for the modern world energy need, wind energy, and wind turbine technology, experienced a dramatic development and mostly considered the fastest growing energy [1].
Within this approach, the wind energy is labialized as one of the world leading energy sources.
This sustainable increase and development in the wind power breakthroughs lead to new requirements and challenges for wind turbine size, wind turbine technology besides the challenges for transmission facilities and integration into the utility grid.

Moreover, the offshore wind power installations have been developed rapidly over the last few years, and the cost for offshore installations declined continuously between 1990 and 2010 with about 90% [1], [2], this trend in cost decline reflects as big challenge in for the turbine technology, installation, and power transmission technology.
And due to the many advantages on the offshore installations as fewer conflicts with the public interest, and more optional wind condition, the future of offshore wind farms is assumed to be a big potential comparing to onshore.
The expectations and potentials are very high in this file as a sustainable energy source and the level of challenges is increased and demands for more offshore economic solutions emerge.

1.1. Motivation and objectives of the study

In this thesis study, the offshore wind farm electrical system is the topic, and the analysis of fault conditions and investigate the protection system, is the research goal.
For this purpose, a typical offshore wind farm electrical system is defined and the main parts of the system include the power generator, power electronic converters and offshore substations which include step-up transformers, reactors, filters, and switchboards.
The power transmission system from offshore to onshore is also a major part of the system which has a big effect on the efficiency of the whole system. This depends on the transmission technology type (AC or DC) then also the connection to the shore grid.

The system will be implemented in DigSilent software from power factory, then a complete study of fault analysis in the electrical system in its both DC and AC side is detailed.
Based on this analysis of the faults conditions, a protection system can be proposed.
Throughout the Thesis, a theoretical analysis of the fault transient performance is detailed with the DigSilent software simulation results for verification.
The purpose of the study focused on having a protection system can protect the wind farm equipment and devices besides the ability to mitigate the influence of the on the connected-on shore grid under fault conditions.

In the following part of this section, the offshore wind farm electrical system is configurated and a fault type is discussed.

1.2. Offshore wind farm configurations

Selecting and design of the wind farm is always influenced by many factors. The technical specifications and cost are mainly the two major factor besides other factors as construction location challenges and maintenance difficulties.
Ad the installation cost for the offshore wind farm is in general high comparing to onshore, so this makes the finance and economic factor is dominants during the engineering stage for an offshore wind farm. A study in Sweden in 2007 and similar to Germany for a survey of failures show that the maximum number of failures happened in the electrical system [1], This put more pressure and demands when building the electrical system and this raises many challenges for engineers and researchers.

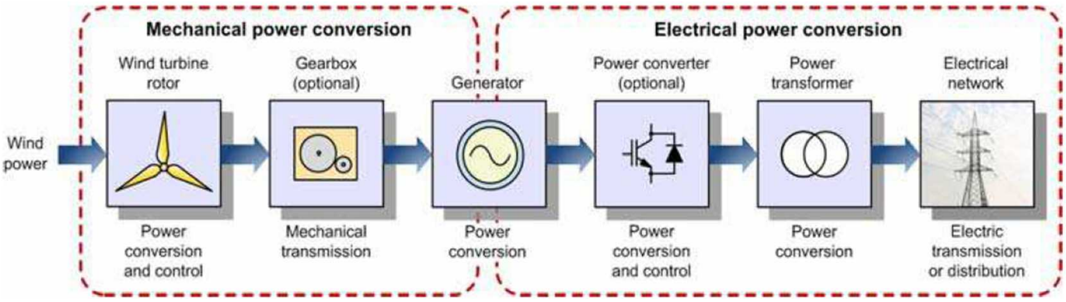

Fig. 1. General description of the wind turbine system [5]

There are many topologies for building a wind farm electrical system, where the system in general consist of three main parts, the generation system, the transmission system to onshore and onshore grid collection system.

With many different wind farm configurations of the electrical system, the main two types are illustrated in the following figures.

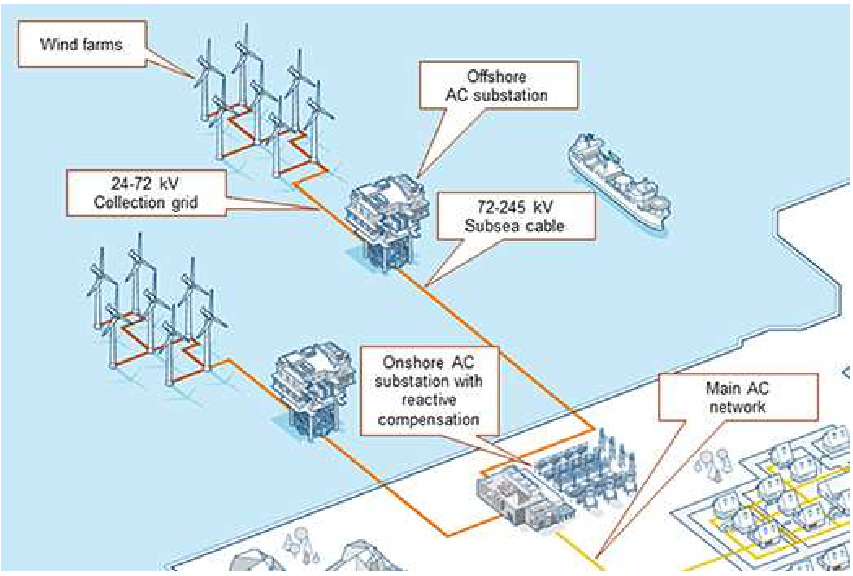

Figure 1.1describes a traditional wind farm System using AC transmission lines.

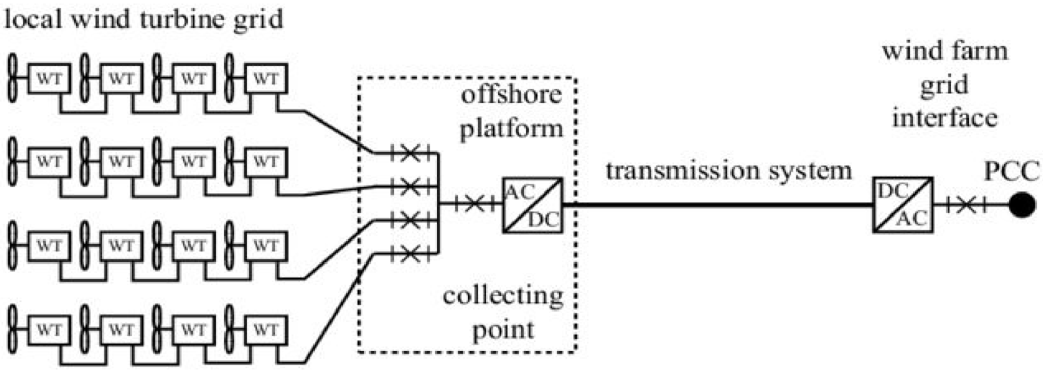

Figure 1.2 describes a traditional wind farm system using DC transmission lines.

More detailed descriptions with advantages and disadvantages for both types will be discussed in Item 1.3.3.

1.2.1 Generation systems

The wind generation system is constructed of two main parts, the turbine, and the generator.

1.2.1.1.Generators

The generator is considered the second main item in the wind generation system and during the history of the offshore wind farms is been defined as the multi-type of generators. In this section, 5 types of generators will be discussed briefly, while more detailed discussion will be expended only for the used one in the wind farm model.

A- SCIG Squirrel- Cage induction generator

The squirrel -cage induction generator is, in general, the most popular in this field, for multi advantages as working without slip rings and no excitation system need besides the low manufacturing cost, low weight and low maintenance cost [6]

On the other side, to stabilize a rotor magnetic field for the generator, the system needs a source of reactive power [5], which in any case can be a capacitor unite, benefiting from the new power electronic [7] to inject the needed reactive power to the generation system.

But with some specific needs relating to speed (3600 p.m., 60 Hz, 2 pole generator) [2] this type of generators should rotate above the synchronous speed [10] to be able to generate power otherwise it will work a motor and consume power.

The SCIC's offer a robust design and by using a power electronic drive, the generator can be improved to work at sub-synchronous speed.

The drive should be full rated power, and this can be a disadvantage of these type of generators. Figure 1.3 shows a standard SCIG.

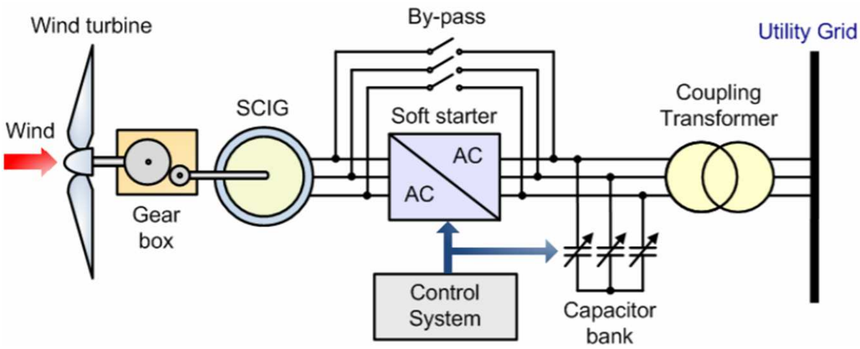

Figure 1.3 Fixed speed wind turbine with a direct connection to the grid through SCIG [5]

B- WRIG Wound-rotor induction generator

In this type of generator, is connected directly to the grid, where the rotor is connected to a variable speed resistance which can be controlled by using a power converter. By controlling the rotor resistance, the slip of the generator is varied.

The WRIG is used in what is called a limited speed system, where the limited speed variation is implemented and also the slip ring can be replaced by a kind of optical coupling [5].

As for disadvantages of this type are the speed variation rage is depending on the size of the variable resistor, besides the need to an external reactive power source as it can not support the grid alone.

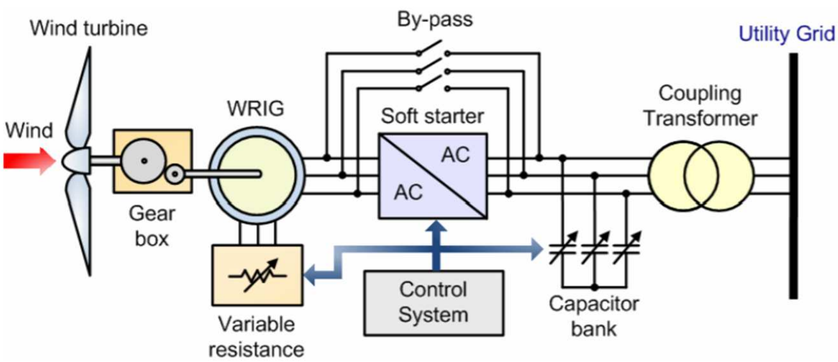

Fig. 1.4 Limited speed wind turbine using a WRIG [5]

C- DFIG Doubly-Fed Induction Generator

This system is one of the most popular generation systems [7] with multi-megawatt variable speed wind turbine, the concept is depending on a back to back voltage source converter which consists of two bidirectional converters sharing a common DC link, one connected to the rotor and the other connected to the grid [7] with a wound rotor induction generator (WRIG), the gearbox is part of the system to couple the rotor to the generator, as to compensate the difference speed range between the rotor and generator. The stator is directly connected to the grid while the rotor winding is connected via a slip ring to the three-phase AC/DC/AC converter. The converter is partially scaled rated of the nominal generated power (Approximately 30%) [5].

The use of the converter is major for enabling the wind turbine to work at a variable speed, which allows for more effective power capture, thus permits to achieve optimal aerodynamic efficiency by tracking the optimum tip-speed ratio of the turbine.
in figure 1.5, we can see a variable wind turbine connected directly to the grid through a double-fed induction generator with a partial scale converter.

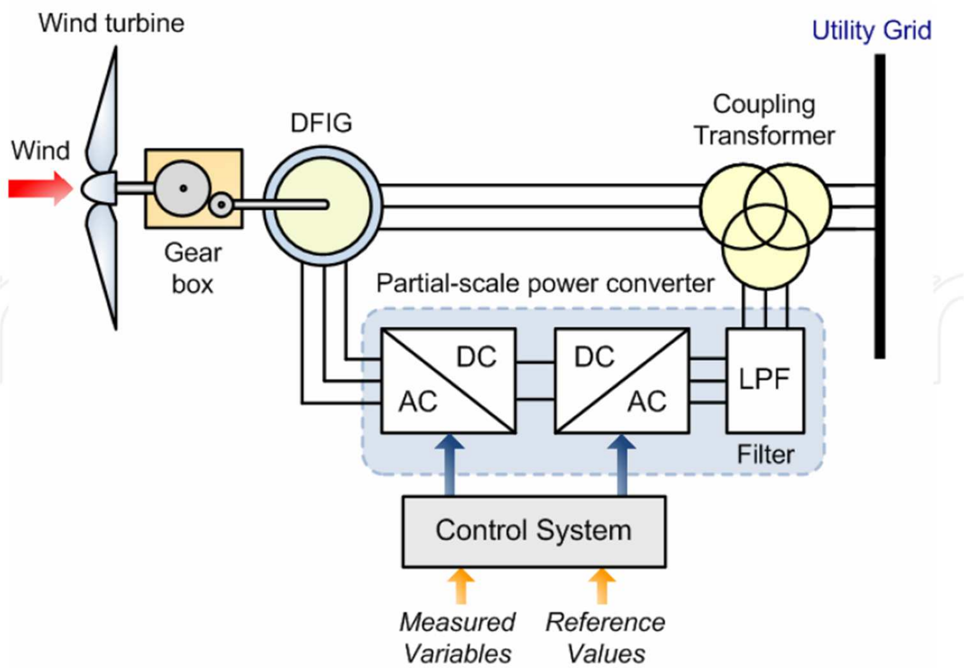

Figure 1.5 Variable speed wind turbine connected directly to the grid through a double-fed induction generator with AC/DC/AC converter [5]

Using a variable speed system leads to less mechanical losses beside the using a smaller power converter makes this concept from an economical point more attractive for the investors as a balance between cost and performance. While using the slip-ring in connection to the rotor can be considered a drawback for the maintenance cost point of view, besides its vulnerability to grid disturbance and fluctuation [8]

D- PMSG Permanent magnet Synchronous Generator

The synchronous generator is excited by permanent magnets or by external dc sour. The PMSG has a high interest in the application of direct driven wind turbine generator without a gearbox, and this is a recent development topology for large- scale wind power generation systems.
The synchronous machines driven by a wind turbine are not supposed to be connected directly to the power grid because of the requirement of the specific damping in the drive train [7].
The PMSG is used for its simple winding structure and essay control [8], the system has besides the multipole PMSGs fully rated converters connecting the wind turbine generation system to the electrical grid. This converter decouples the generator from the grid.
The full- scale power converter transforms the variable frequency alternative power produced by the PMSGs into a fixed AC frequency power and also allow locally generated reactive power compensation control.
The converter system is constructed of two converters, grid side converter and stator side converter, both converters are IGBT-based, and connected via DC link.

Thus the generator electrical frequency may change relating to the wind speed while the grid frequency remains without changes.
The grid side converter is controlled to enable the system to control the reactive and active power, while the stator side converter allows control of the generator operation to extract the maximum power from the available wind velocity [6].
Figure 1.6 shows the variable wind turbine with a permanent magnet synchronous generator with full scale- back to back voltage source converter.

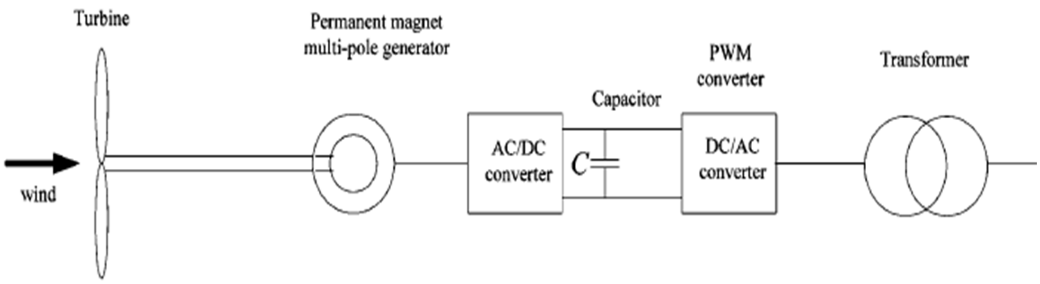

Figure 1.6 Variable wind turbine connected directly to the grid via permanent magnet synchronous generator PMSG [7]

E- Electrically excited synchronous generator EESG

The electrically excited synchronous generator is applied in wind turbine generation system recently. In the EESG, the control system is more complicated as the stator flux and the rotor current has a major effect on the electrical torque.

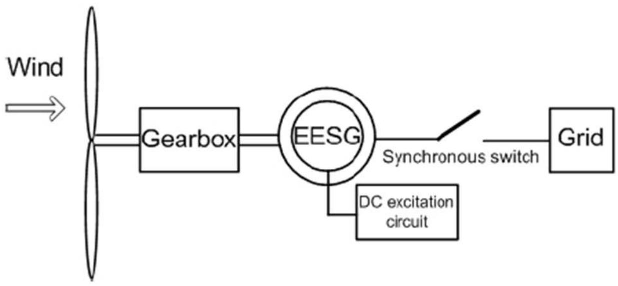

Figure 1.7a Shows fixed speed EESG Electrically excited synchronous generator with the gearbox.[8]

As described in the figure 1.7a, the EESG is directly connected to the grid through a synchronous switch, where this can eliminate the need for converter as the generator voltage has a wide range of control 4,16/ 13.8 KV [8]

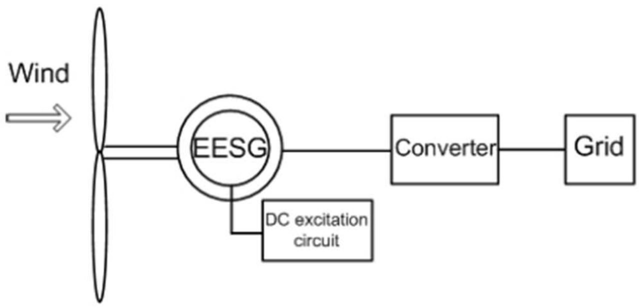

Figure 1.7b shows Direct drive EESG Electrically excited synchronous Generator

As figure 1.7b shows a direct drive EESG with full rated converter [8]

This type of generator has low efficiency besides the complicated rotor construction[10]

1.2.2. Wind Turbine

The power fraction captured from the wind available power is defined by the turbine design and control. The power available from the wind is given:
$P_w = 0.5\ A\ D\ V^3$
A: is the swift area of the turbine
D: is the air density
V^3: is the cube of the wind speed flowing through the turbine
Then the turbine power P_t is given
$P_t = C_p.\ P_w$
$C_{P:}$ is the fraction power coefficient.
The coefficient depends on the turbine design with a maximum mathematical value of 59% (Betz limit) [1].

1.2.3. The onshore Grid collection system

The connection of the wind farm electrical system resource to the onshore grid system is conditioned by many criteria and has to be in the very first a high-quality electric power where should be in the same time reliable and flexible and also be efficient to a high state level.
Besides that, the requirements also to meet the voltage amplitude and frequency of almost stiff onshore utility distribution grid.
The type of connection depends on the wind farm generation system and transmission systems.
The old traditional way (Danish way) [5], where the turbine rotor is connected to the induction generators shaft through a fixed ratio gearbox at any operating point.
In this case, the induction machine is connected directly to the three-phase network, and the operation of the turbine is primarily at a constant speed.

The new modern way of connection is for variable speed operation, where is possible, by using of a new power electronic device, to make blade pitch angle control, besides the possibility to using the variable generator rotor resistance.
In this case, the connection to the grid can be, for a direct driven PMSG, through a direct online a full-scale power converter, or through a partial-scale power converter for doubly-fed induction generator DFIG as explained before.
Mostly the connection to the grid is done through a step-up transformer, and for some applications where used a DC transmission lines and a voltage source inverter, benefits from a low pass filter to mitigate the perturbation in the distribution system [5] from harmonics generated by the pulse width modulation unite PWM high- frequency switching.

1.2.4. Transmission system:

As the offshore wind farm size and distance to shore increased constantly, The importance of the role of the transmission system in the offshore electrical system starts to attract high attention considering that the load is mostly on shore.
Mainly, two option to transmit the power from offshore to onshore are available, the traditional high voltage alternating current HVAC system and the high voltage direct current HVDC system, and besides that, there are some different ways to apply that.

The two HVAC and HVDC technologies are quite different, where both options concepts have their own conditions besides the advantages and disadvantages.

1.2.4.1. HVAC High voltage AC system

The tradition transmission system to transmit the offshore power to onshore. Since the main power grid is built around this AC technology and for economic reasons, the HVAC transmission system is still used in the most commercially offshore wind farms to connect the farm to the onshore grid [11], while some farms an offshore substation is been used.

The HVAC system is constructed beside the turbine, a set of 3 core cable (or several cables in parallel) as necessary to load a big quantity of power to onshore, and for some applications (long distance to shore) an offshore substation which includes step-up transformers and the reactive power compensation is used, an onshore substation which also include a step-up transformer and reactive power compensation, an AC connection point(The common flow point where all collected power from WF flow through it [11].

For some wind farms where the distance too shore is short, the offshore or onshore substation may not be necessary.

Also to be able to provide a voltage control, a kind of dynamic reactive power compensation (STATCOM, SVC) is used.

Figure 1.8shows a traditional HVAC wind farm system

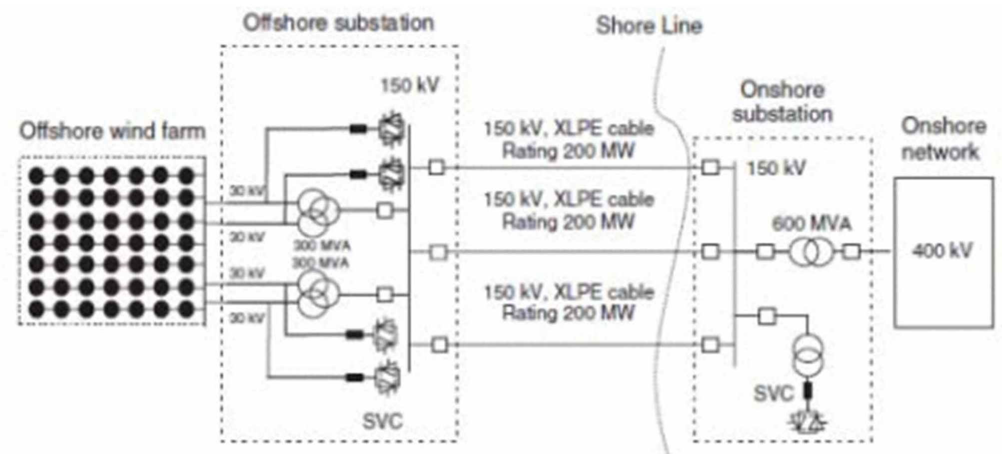

Fig. 1.8. Example of traditional HVAC wind farm system [13]

1.2.4.2. HVDC High voltage DC system

The use of a DC transmission system is the main alternative of the AC one, where power electronic converters are used to convert AC to DC and vice versa.

As the distance to shore increases, a new solution coming forward, A HVDC transmission option was a solution for the disadvantages of long long distances and its negative consequences on the system, an HVAC option is used as transmission lines form offshore wind farm to shore.

HVDC can be a practical option to connect an offshore wind farm with more than 100-150 Km from shore[14] were using this technology offers many advantages as large and long distance wind farm to be integrated.

- The offshore wind farm and the grid are decoupled by a kind of asynchronous link, sol will not be a direct effect especially under fault conditions.
- The power flow is easy to define and control.
- The technical limits of using AC cable which reduces the capability to transmit the AC active power is not existed by using DC cable (no cable charging currents).

- Less power loss by using a DC cable and more caring capacity [14].

HVDC has two types of technologies, the line-commutated converter HVDC (LCC HVDC) using thyristors and the Source voltage converter based HVDC (SVC HVDC) using IGBT's Figure 1.9 shows a general single line diagram for HVDC wind farm.

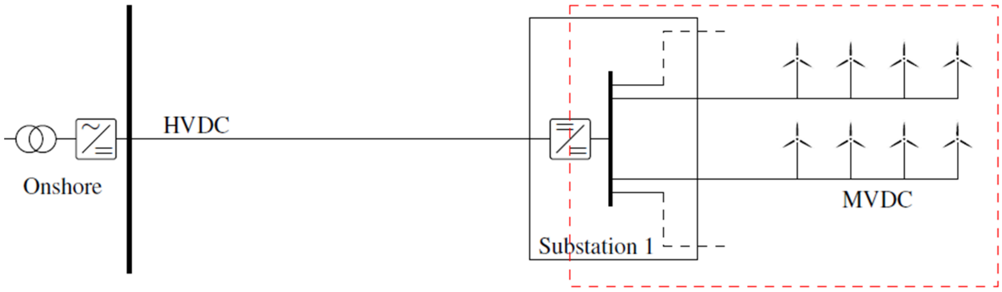

Fig. 1.9 A standard HVDC system configuration

HVDC transmission system, come up with some extra added cost for the needed converters stations at both ends, onshore connection to grid and the off wind farm side, besides that an additional losses due to switching losses are experienced and the total transmission losses are larger than the HVAC system, even the losses in the DC cables are less the AC one [15].

A- Voltage-source converter based (SVC HVDC)

A voltage source converter using IGBT's allow the transmission to have many advantages;

- The active and reactive power control is controlled independently.
- For operation, the system is self-commutating and does not require an external voltage source [14].
- In case of low wind, it allows to transmit the AC power to the wind farm and the control of the AC power is allowed in both ends.
- Comparing to LCC, the SVC operates at a higher frequency which means a less harmonic production [15], but considerably higher losses which can be a negative aspect for this system.
  Figure 1.10 shows a transmission system for a wind farm using an SVC HVDC.

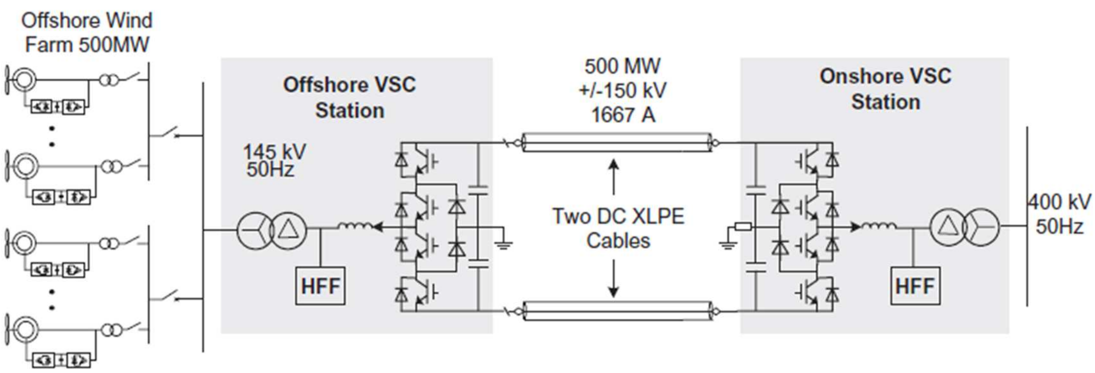

Fig. 1.10 A wind farm connections system using HVDC VSC with high-frequency filters.[14]

Under normal operation, the concept of the VSC transmission system is to keep the DC voltage on the DC link at a constant value, which means the exchange of the active power is balanced between the two system ends [14].
The offshore VSC main function is to collect the available energy from the generators, at the same time control the frequency and voltage, maintain them at the desired values on the offshore AC network [14], thus the offshore converter works as a slack node, it absorbs the power fluctuating in the offshore wind farm[15].
The onshore SVC assigned function is to control the DC voltage assuring that the energy collected by the offshore VSC station is transmitted to the AC network distribution grid.

The balance in the circuit is maintained by the offshore VSC, it regulates the DC voltage which affected by the fluctuation power collected by the offshore VSC from the wind turbine. The sensitivity of the SVC for overcurrent affects its current capability and make it limited, which consider the main drawback for this system, as even for short period the overcurrent causes thermal stress which can lead to a degrade of even damages in the switching elements. Under fault condition in the grid, the voltage temporally is reduced, the power can be transmitted to the AC grid is reduced as the current is limited. The onshore SVC is not able anymore to regulate the DC voltage. This leads to quick action required to reduce the generated power in the turbine station, and there are many strategies can be discussed to do that.

B- Voltage Source converter LCC based using Thyristors.

A source voltage converter using Thyristors is called also a line-commutated converter, this type of converter requires an auxiliary AC voltage source for commutation [14]. On the offshore station, The reactive power source can be either a VSC -based STATCOM or a synchronous compensator. For on the shore, a reactive power compensation by a normal filter can be used.
The robustness with high capacitance to many MW is considered as main advantages of this system, while the additional space, weight, and size are considered as disadvantages.
At the offshore station, the converter and the STATCOM absorb the active power provided by the wind farm turbine and transmit it to the onshore converter.
Figure 1.11 shows an offshore wind farm with HVDC LCC converters.

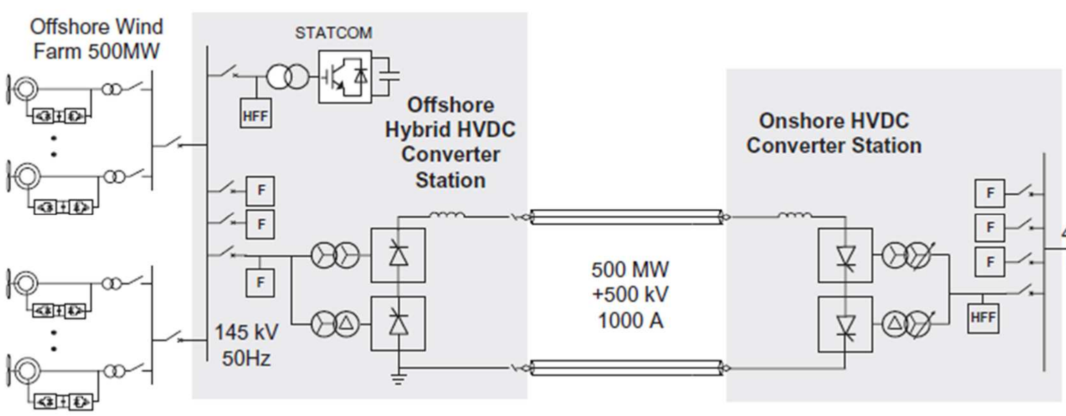

Fig. 1.11 A wind farm connections system using HVDC LCC

The STATCOM DC voltage link is affected and vary by an imbalance between the generated active power and the transmitted one by the HVDC converter, thus this capacitor voltage works as an indicator and is used to change the current order of the converter to maintain correct DC voltage value of the STATCOM [14]

C- Multi-terminal DC wind farm network (MTDC)

Nowadays, one of the concerns is the limited power exchange between many countries, where offshore wind farms are located close to many countries.
The multi-terminal dc network is one of the solutions, where is required the connection to more than two terminals to a common DC bus.
Since HVDC LCC is considered as complicated so high for having different operating mode joined with complicated control system [15]. Hence maintaining a balance of the power is DC network and the slow reaction to the fault in the AC side is a challenge.

On the other side, SVC DVDC gives more possibility and ease in the MTDC, in the VSC MTDC the possibility to change the power flow direction is achievable without changing the polarity [16], which makes it easy to add more terminals to the VSC MTDC. This opens many possibilities to connect much offshore wind farm to gather and the connection to multi AC gird is possible.
Figure 1.12 shows atypical VSC MTDC system

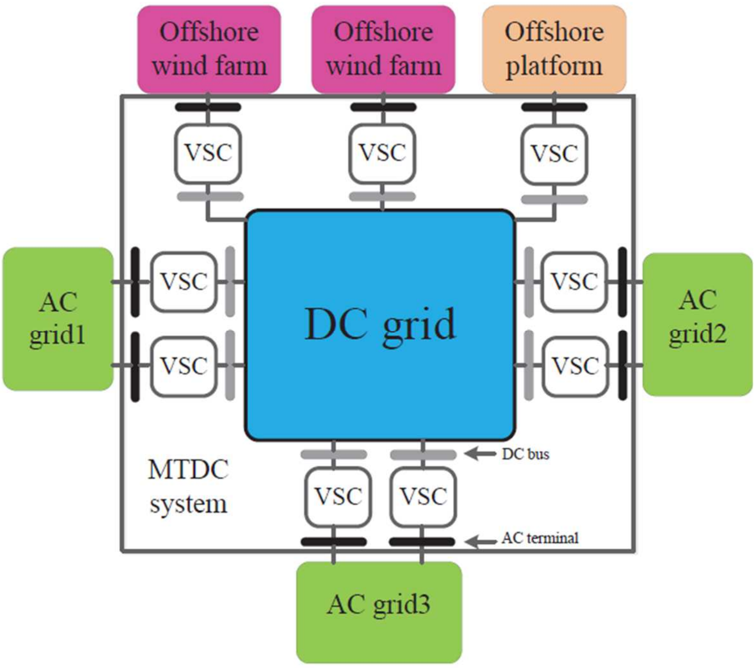

Fig. 1.12 A typical SVC MTDC system

In SVC MTDC, controlling the dc voltage, interactions between converters and power flow are the challenges. Since overvoltage can lead to damage in the electronic equipment of the converters, low DC voltage results into decreasing the constructability of the converter, therefore, maintaining the DC voltage in the acceptable range is a key challenge for VSC MTDC system [16]. Consequently, increasing the active power into the DC grid by the converters more than the extracted active power from the inverters will result in a high Dc voltage.
In SVC MTDC, the converters are to be provided with a direct voltage drop characteristic, which allows the regulation for the amount of injected/ absorbed active power in the system,

thus the fluctuation from the injected power from interconnected wind farms can be equally distributed [15].

1.3. Fault analysis and protection

For offshore wind farms, The fault analysis, and protection design are required in order to provide enough information for an optimum selection of the protection schemes, switchgear, the setting of relays and stability system operation, where faults are considered as isolation frailer, flashover or human error.

For different fault conditions, the system behavior will be different, the protection requirements are also different as the system configuration changes, then In order to quantify the protection requirement and needs, a detailed fault analysis should be discussed for a specific wind farm system configuration.

1.3.1. Faults Types

The faults in the offshore wind farm electrical system should be detected and for safety purposes isolated, this should be done fast enough for the wind turbine work stability through the fault condition.

In general, different fault conditions are identified in an offshore wind farm, thus the behavior of the electrical system of the offshore wind farm is discussed for each fault condition.

A detailed fault condition discussion and analysis study is performed by the DigSilent software and for the final model of the wind farm only considered for this study.

A different protection zones such terminal level zone, network level zone, and transmission line zone are discussed and for each zone, a different fault type is considered for each.

1.3.1.1. The line to line fault (LL)

The fault type can divers between the wind farm electrical systems, and according to the generator type and the topology used for transmission of the power within the AC or DC system.

- For the AC system, two or three phases in a symmetrical manner, when a short circuit happens, a large short circuit current is initiated in the system. The behavior of each zone during the fault condition can be understood by developing an equivalent circuit, thus a detailed calculation of the short circuit current is possible, and the behavior of the healthy terminal is also a major interest under faulty system instability status.
  Many investigations presented that the grid three-phase fault can have the largest impact [17] on the mechanical system of the turbine.

- For the DC system, the short circuit fault (Pole-to-pole), the positive pole is connected directly to the negative pole (with the possibility to be connected to ground).
  This fault is described as a low impedance fault and could have a severe impact on the other system parts since the fault current increases rapidly after the fault occurs [19]
  In this type of faults, (Pole to pole or pole to pole to ground) during the fault condition, all the capacitors connected to the faulty part will discharge to the fault path[19]and this leads to a high current flow in the faulty section components, which is comparable to the three-phase fault to ground in AC electrical network, while the rising rate of the faulty current in DC is higher than the AC [19].
  Figure 1.13 shows a different type of faults in the DC system

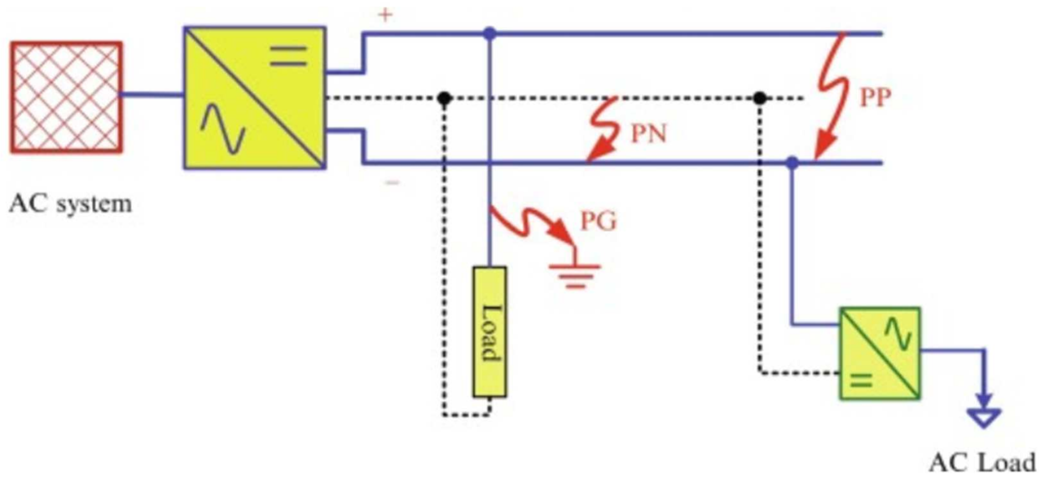

Fig. 1.13 shows a different type of faults in DC System

the converters are a major part to be considered, using the control of the converters in a way to imitate the negative effects of the fault on the system.

1.3.1.2. The line to ground fault (LG)

<u>For AC System</u>
this type of fault is common where the insulation of some cables is broken, thus a short circuit occurs with the earthing system. The value of the ground fault current is depending on the type of the associated earthing system considered.
The grounding system har a direct effect on the grounding fault current, whereas the phase to earth voltage increased relatively on the two healthy phases as the faults occur
A different method is known for grounding systems [18] for offshore wind farm:

- Isolated grounding system: no direct connection to the ground. And the single-phase earth fault current is relatively smaller than the short circuit current.
- Direct grounded system: the single-phase earth fault current is large
- Reactance and resonance grounding system: the transformer neutral is connected to the ground through a reactance: the single-phase earth fault current is reduced by the connected reactance.
- Resistance ground system: in this case, the transformer neutral is connected to ground through a resistance, this system can result in earth fault case by reducing the magnitude of the fault current and at the same time mitigate the transient destructive effect of the overvoltages [18].

<u>For the DC system</u>
this fault occurs when one of the two poles, the negative or the positive one, of the dc System) is connected directly to ground.
For Dc system, the pole to a ground fault has less effect on the Dc network, since one of the poles only participate in the fault current in comparison with the pole-to-pole fault.
As the fault pole-to-ground occurs, in general, through a fault impedance, this leads to mitigate the rising rate consequently, thus limiting the fault current magnitude [19].

1.3.1.3. Open Circuit OC

An open circuit OC fault occurs due to breaking on the cable or also a consequence of another fault condition (Short circuit)

An OC fault in the side of the converter can degrade the power quality and simultaneously can lead potentially to another secondary fault [20].

1.3.2. Protection Zones

The protection zones for the wind farm system is relatively connected with the wind farm electrical system configuration.

The consequences and the major effects on the faulted zone equipment beside the healthy part are studied based on the system configuration parts. The wind farms.

1.3.2.1. HVAC system protection zones

The high voltage AC protection zones can be divided into major parts [21]:

- Wind turbine general zone associated also with its power electronic converter and control.
- The collector feeder
- The collector bus
- High voltage transformer
- Transmission line
- Capacitor bank (Filter)

These zones classifications and division can be diverse according to the system design and configuration.

Figure 1.14 shows an example of the protection zones, for a wind farm turbine using an AC system as a transmission line.

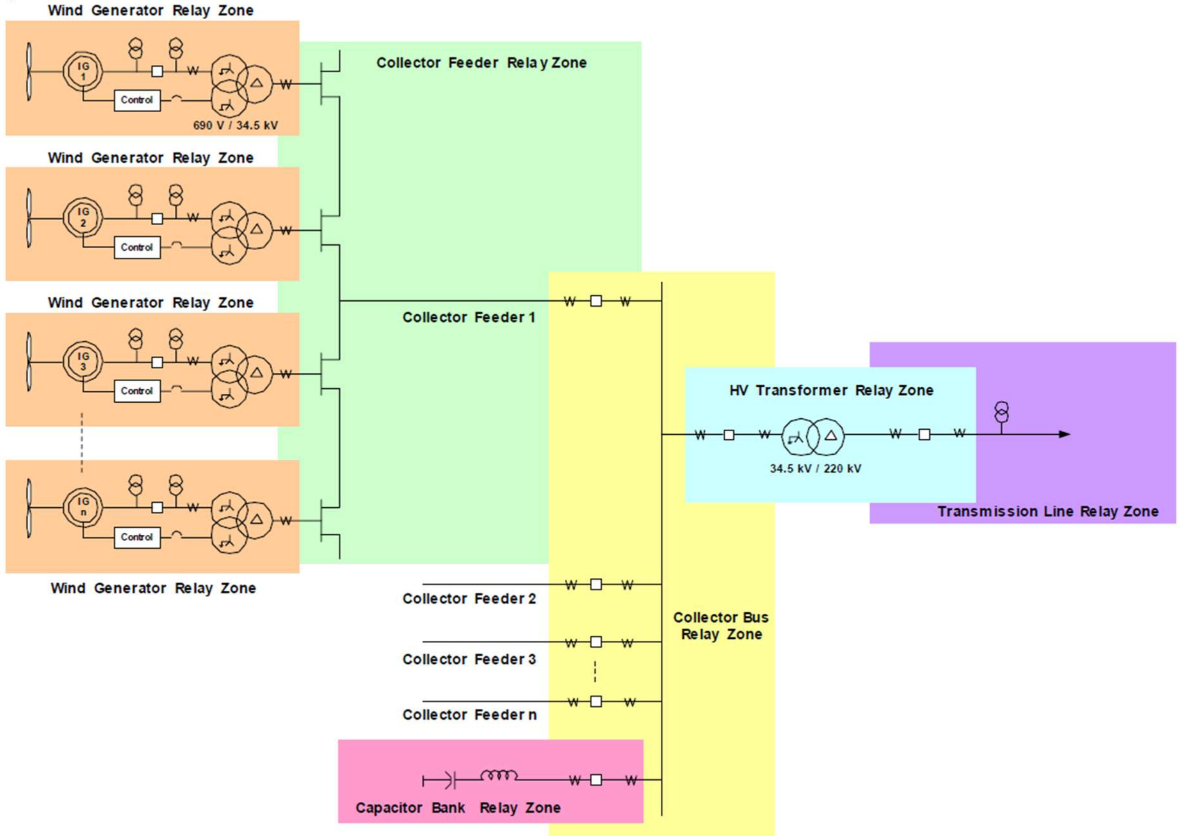

Fig. 1.14 example of wind farm protection zones [21]

Since different topologies for connecting the collection feeder to the wind turbine generator are used, the protection of the wind farm is considered as a large challenge, and using the different topologies such, Radial, feeder-Sub-feeder, bifurcated radial and looped feeder [21] affects the fault detection methods and protection facilities.

1.3.2.2. HVDC system, the protection zones

The HVDC protection zone is classified into three different zones [22]:

- Terminal-fault level: when the fault occurs before the terminal circuit breaker, is specified as a terminal-level fault. The faults as specified in 1.2.1 can be LL, LG and OC type.
- Network level: faults occurring after the terminal breaker to the collector bus named as a network-level fault.
- Transmission level: the fault occurs in the transmission line named as transmission lines fault. This fault (LL or LG)is specified as a major fault since the wind farm system cannot be operated under transmission line fault [22]. The fault over current results can result in serious damages the system especially the power electronic parts in both sending and receiving an end of the wind farm if the fault is not isolated on the proper time.

Chapter 2

2. Modeling

As described in the previous chapter for HVDC offshore wind farm, due to better control capabilities, options and characteristics, the DFIG double-fed induction generators as variable-speed wind turbine considered as a promising solution for future wind farm technologies' applications.

In this chapter will go through the mathematical model for the base case HVDC wind farm, with more focus on the electrical system than the mechanical part system.

In our study, the DFIG is been selected as the generator for the wind turbines used in the wind farm considered configuration, and based on that, the wind farm configuration is been selected as follows:

- The mechanical system includes the wind turbine and the gearbox.
- The wind turbine generators equipped with a Doubly fed induction generator DFIG
- The wind turbine is connected via a source voltage converter high voltage direct current VSC HVDC.
- High voltage direct current transmission lines.
- The Transmission line is connected to the onshore station via a source voltage converter high voltage direct current VSC HVDC (Inverter).
- A step up transformers are been applied in both sides, Sending terminal and receiving terminals.
- Controllers and PLL are also part of the electrical system

A general scheme shows the wind farm main configuration as per the figure.

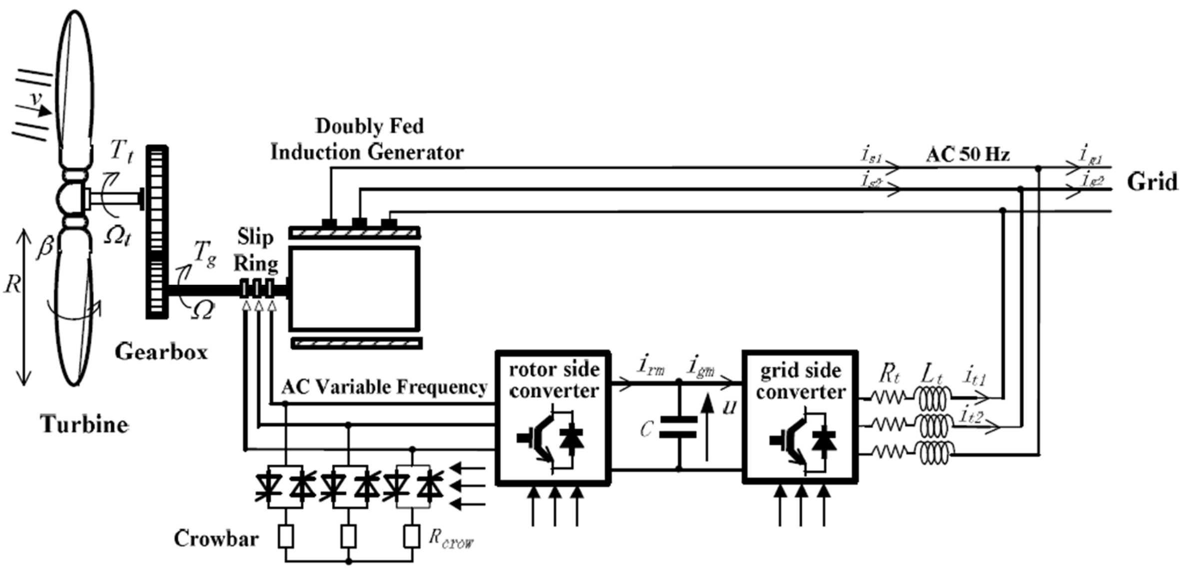

Fig. 2.1 Doubly fed induction generator side DFIG with an example of crowbar protection

2.1. Aerodynamic Modeling (Mechanical parts)

The aerodynamical torque can be given by the following equation 2.1:

$$T_t = C_p(\lambda,\beta)\frac{\rho S}{2}v^3\frac{1}{\Omega_t} \quad (2.1)$$

Where this torque is characterizing the wind turbine.
Ωt: the angular speed of the turbine.
S: The swept area of the turbine.
v: The wind speed.
ρ: The air density.
The power coefficient Cp(λ,β), as it represents the wind turbine aerodynamic efficiency, it depends on the design of the blade (the pitch angle of the blades β and the tip speed ratio λ) [27].

where two mass constructs the drive train, a big one reflects the large turbine rotor inertia for (Blades and hub) and a small one representing the generator rotor mass. thus, the model includes the big mass turbine rotor inertia only, as it has a more considerable effect on power fluctuation.
The first order differential equation for the acceleration model can be written:

$$J\frac{d\Omega}{dt} = Tt - Tg - f\Omega \quad (2.2)$$

J: The total inertia of the equivalent shaft.
T_g: The torque from the gearbox.
f: friction coefficient of the equivalent shaft.

The aerodynamical power of the slow wind turbine shaft is transferred to the fast speed generator shaft by the gearbox with a gear ratio G, it defines the mechanical speed of the generator Ω.
The mathematical description by the following equation (2.3):

$$T_{em} = T_g/G$$
$$\Omega_t = \Omega/G \quad (2.3)$$

where T_{em} is the generator electromagnetic torque[27].

2.2 Modeling of the DIFG

The doubly-fed induction generator used for variable speed wind turbine, and unlike the other generator types, the DFIG delivering power to the grid by using both terminals of the stator and rotor. while the stator is connected directly to the grid, the rotor is connected through a back to back power electronic converters.

the equivalent circuit of the DFIG van be seen in the figure (2.1) where the magnetizing losses are included, If the DIFG is delta connected, still the machine can be represented by equivalent star (Y) Representation [26]:

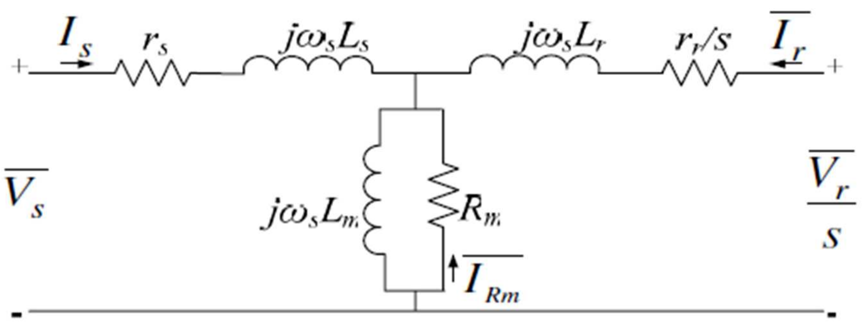

Fig. 2.1 Doubly fed induction generator equivalent circuit.[26]

where if the rotor side voltage is short-circuited then the equivalent circuit of the DFID becomes similar to the fixed speed squirrel cage induction generator SCIG.
A more detailed dynamic behavior of the generator current can be represented by using a fifth order dynamic modeled in two axis d-q synchronous reference frame.
the following equations are given [27]:

$$\begin{aligned}
\frac{d\psi_{sd}}{dt} &= v_{sd} - R_s i_{sd} + \omega_s \psi_{sq} \\
\frac{d\psi_{sq}}{dt} &= v_{sq} - R_s i_{sq} - \omega_s \psi_{sd} \\
\frac{d\psi_{rd}}{dt} &= v_{rd} - R_r i_{rd} + \omega_r \psi_{rq} \\
\frac{d\psi_{rq}}{dt} &= v_{rq} - R_r i_{rq} - \omega_r \psi_{rd}
\end{aligned} \tag{2.4}$$

where R_r, R_s, L_r, and L_s are the resistances and inductances of the rotor and stator winding, and V_{rd}, V_{rq}, V_{sd}, V_{sq}, I_{rd}, I_{rq}, I_{sd}, I_{sq} are the *d* and *q* components of the space vectors of the voltages and currents for the rotor and stator. while ωs is the synchronous speed and ωr is the rotor speed

where also for the flux we use the following equations (2.5):

$$
\begin{aligned}
\psi_{sd} &= L_s i_{sd} + M i_{rd} \\
\psi_{sq} &= L_s i_{sq} + M i_{rq} \\
\psi_{rd} &= M i_{sd} + L_r i_{rd} \\
\psi_{rq} &= M i_{sq} + L_r i_{rq}
\end{aligned} \qquad (2.5)
$$

for these equations, M is the main inductance and ψ_{sd} , ψ_{sq}, ψ_{rd} and ψ_{rq} are the d and q components of the space vectors of the flux.
then the equation of the electromagnetic torque can be expressed by using the stator quantities and P pair-number of poles [27]

$$
T_{em} = p(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \qquad (2.6)
$$

2.3 Power Converters Modeling

For the purpose of modeling of the power electronic converters, the semiconductors considered to be ideal, instantaneous commutation and no power dissipation, the power inverter can be constructed of two ideal witches and three commutation cells.

Then, for each power switch, a switching function S_{ij} can be defined, and it demonstrates the ideal commutation orders where the function can take two values, Value 1 represents a switch state closed and 0 for a switch sate open. and it's considered as a theatrical state of the switch. Both switching functions have a complementary state in each commutation cell. then, in this case, we can rewrite the modulated voltages as a product between the two modulation functions and the DC voltage u, then can be defined as per the following equation [27]:

$$
m = \begin{bmatrix} m_1 \\ m_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} s_{11} \\ s_{12} \\ s_{13} \end{bmatrix} \qquad (2.7)
$$

Then for the rotor side, the modulated voltages and current can addressed in the following equation:

$$
\begin{aligned}
v_t &= m_g u \\
i_{gm} &= m_g^T i_t
\end{aligned} \qquad (2.8)
$$

Using the same concept, for the grid side converter we can write the modulated voltages and current [27]

$$
\begin{aligned}
v_t &= m_g u \\
i_{gm} &= m_g^T i_t
\end{aligned} \qquad (2.9)
$$

2.4 DC bus and filter modeling

The following equation represents the evaluation of the DC voltage for the Dc bus[27]:

$$C\frac{du}{dt} = i_{rm} - i_{gm} \qquad (2.10)$$

AS C is representing the total capacity of the DC bus, i_{rm} is the rotor side filter current, i_{gm} is the grid side filter current

And as for the filter currents, they can derive from the following differential equation:

$$L_t\frac{di_t}{dt} = v_t - R_t i_t - v_g \qquad (2.11)$$

where L_t and R_t are the inductance and resistance of the filer.

2.5 Source voltage Converter HVDC transmission modeling

This topology shows different converges stages, the first stage is needed to control the generator, the second stage is required to step up the DC/DC voltage converter, while the last stage is the onshore part, the converter is required to make the grid integration of the wind farm to the main onshore grid. Figure 2.2 shows an example of a single line diagram for a wind farm grid integration VSC using an HVDC transmission line based on a three-level neutral point clamped NPC converter [30]

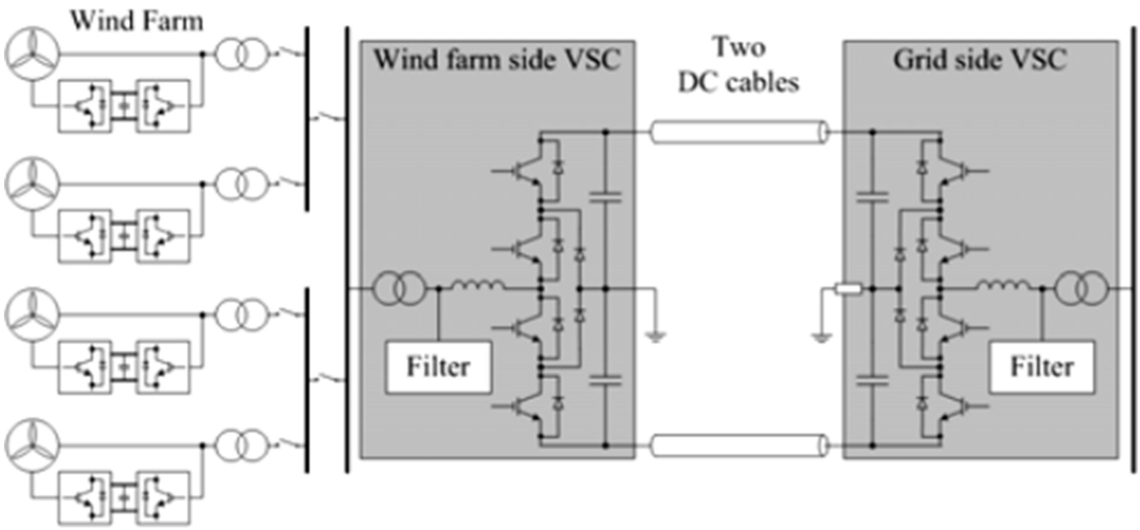

Fig. 2.2 An example of a single line diagram of a wind farm integration using VSC HVDC transmission [30]based on three level converters [30]

The figure (2.3) shows a schematic of a typical VSC -HVDC system [28], the figure shows also the components of the system which consists of the main items [28]:

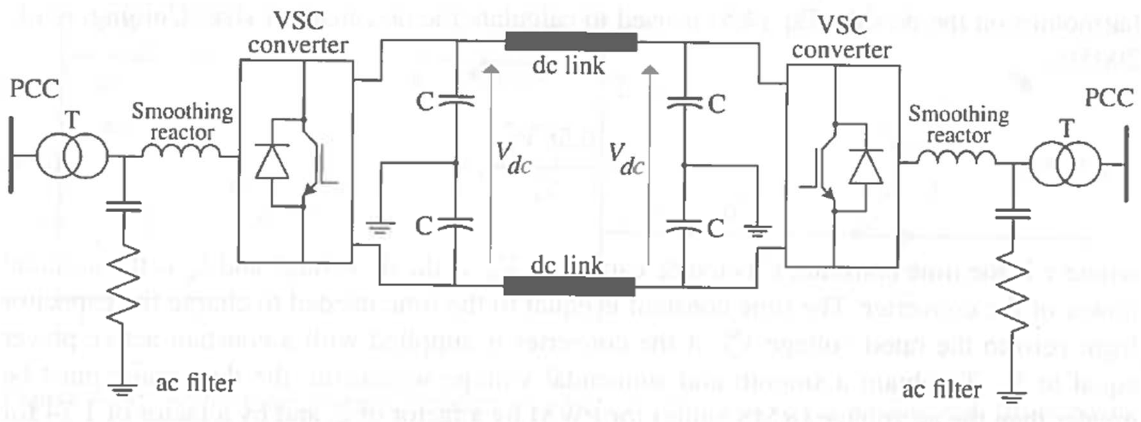

Fig. 2.3 A typical basic structure of VSC – HVDC System [28]

- VSC converters: Using IGBT's switching devices to achieve the requested HVDC level and can have a different type of configurations such two-level converter, three level converter or multi-level converters.
- Coupling transformers: A normal transformer is used, as the filter is connected between the smoothing reactor and the transformer, the transformer is not exposed to harmonics or dc voltage.
- Smoothing reactor: It acts a harmonic filter, reduces the currents and voltage harmonics and limits the short circuit current, and it eases controlling of the reactive and active power flow by adjusting the currents through them.
- Harmonic filter: a passive high pass filter are only needed to eliminate the high order harmonics, produced by the switching IGBT's using a high-frequency PWM.
- DC capacitor: two same size capacitors at the end of the DC sides, with the main function to keep the power balance during the transient conditions, also to reduce harmonic on the Dc side
- DC cable: A DC XLPE cables are preferable because of low weight, flexibility, and good mechanical strength.[28]

2.5.1 The VSC- HVDC dynamic model:

As the fig. (2.4) shows the typical transmission system basic structure of VSC/HVDC, the converter on the left side is (VSC_1) is supposed to operate as rectifier to transform the power from the source of AC side to the voltage source converter DC side VSC while the right side converter (VSC_2) is assumed to work as inverter to transform the power from the VSC dc side to the ac side.

The AC power currents are denoted (i_{sa}, i_{sb},i_{sc}) flow from the ac power source to the VSC converter or vice versa and the AC power voltages (v_{sa}, v_{sb}, v_{sc}) are three ideal sinusoidal waveforms.

At the VSC terminals, the currents and voltages are (i_{ca}, i_{cb},i_{cc}), (v_{ca}, v_{cb}, v_{cc}) respectively R_F, L_F, L_F is the coupling reactor resistance and inductance and R_T, L_T is the coupling transformer resistance and inductance.

For the DC side, is modeled as a series circuit of resistance and inductance R_{dc}, L_{dc} where I_{dc}, V_d is the dc link voltage and current, C is the dc link capacitor.

The subscript 1 and 2 are for sending and receiving end respectively.

we can conclude the following equation based on Kirchhoff low, considering all the quantity per unit and the time in second [28]:
for rectifier side, where $R_1 = R_{T1} + R_{F1}$ and $L_1 = L_{T1} + L_{F1}$

$$\frac{di_{sabc}}{dt} = -\frac{R_1}{L_1} i_{sabc} + \frac{1}{L_1}\left(v_{sabc} - v_{cabc}\right) \tag{2.12}$$

And for inverter side, where $R_2 = R_{T2} + R_{F2}$ *and* $L_2 = L_{T2} + L_{F2}$

$$\frac{di_{sabc}}{dt} = -\frac{R_1}{L_1} i_{sabc} + \frac{1}{L_1}\left(v_{sabc} - v_{cabc}\right) \tag{2.13}$$

By using the park's transformation for the equations (2.12) and (2.13) to simplify the design, the three-phase quantity can be written:
- for the rectifier side:

$$\begin{aligned} \frac{di_{sd1}}{dt} &= -i_{sd1}\frac{R_1}{L_1} + \omega i_{sq1} + \frac{1}{L_1}\left(v_{sd1} - v_{cd1}\right) \\ \frac{di_{sq1}}{dt} &= -i_{sq1}\frac{R_1}{L_1} - \omega i_{sd1} + \frac{1}{L_1}\left(v_{sd1} - v_{cd1}\right) \end{aligned} \tag{2.14}$$

the inverter side:

$$\begin{aligned} \frac{di_{sd2}}{dt} &= -i_{sd2}\frac{R_2}{L_2} + \omega i_{sq2} + \frac{1}{L_2}\left(v_{cd2} - v_{sd2}\right) \\ \frac{di_{sq2}}{dt} &= -i_{sq2}\frac{R_2}{L_2} - \omega i_{sd2} + \frac{1}{L_2}\left(v_{cd2} - v_{sd2}\right) \end{aligned} \tag{2.15}$$

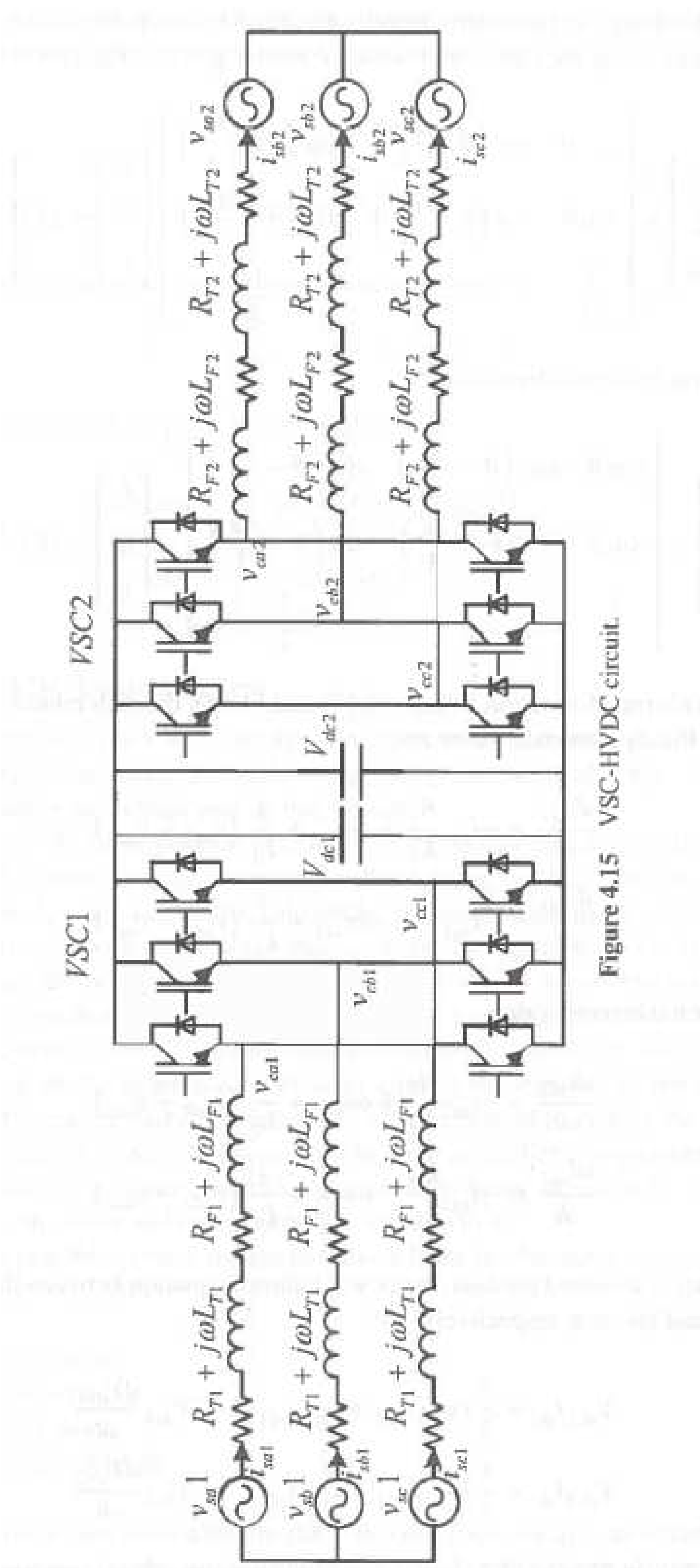

Fig. 2.4 Typical transmission system basic structure of VSC-HVDC system [28]

The power balance equations can be written between the both dc and ac sides for rectifier and inverter side respectively considering the converter has no losses:

$$V_{dc1}I_{dc} = \frac{3}{2}\left(v_{cd1}i_{sd1} + v_{cq1}i_{sq1}\right) - CV_{dc1}\frac{dV_{dc1}}{dt}$$
$$V_{dc2}I_{dc} = \frac{3}{2}\left(v_{cd1}i_{sd1} + v_{cq1}i_{sq1}\right) + CV_{dc2}\frac{dV_{dc2}}{dt} \qquad (2.16)$$

The equations 2.14, 2.15 and 2.16 are the dynamic equations modeling the VSC-HVDC.

Thus, the instantaneous total power can be written in the time domain:

$$S(t) = v_a(t).i_a(t) + v_b(t).i_b(t) + v_c(t).i_c(t)$$

and similarly, by using Park transformation total power can be expressed [28]:

$$p(t) = \frac{3}{2}[v_d(t).i_d(t) + v_q(t).i_q(t)]$$
$$q(t) = \frac{3}{2}[-v_d(t).i_q(t) + v_q(t).i_d(t)] \qquad (2.18)$$

Chapter 3

3. Wind farm models in power factory and fault analysis.

In this chapter, the detailed offshore wind farm configuration will be discussed in details and the system behavior during the fault conditions will be defined in different points and locations in the system, this will include different cases relating to the fault location in the onshore part, the offshore part, and the DC transmission lines.
As a starting point, a brief description of the power factory calculation software (DigSilent) will be introduced and a brief view of the models of the main items as defined in it.

3.1 Wind farm modeling in Power factory (Digsilent)

The power factory calculation software is a leading power system analysis software application for use in analyzing different types of systems, generating systems, transmission systems, industrial and distribution systems.

A full range of functionality has covered by the software, from simple features and standard applications to more complicated and advanced application and also highly sophisticated applications including distributed generation, wind power, real-time simulation and also performance, monitoring of system supervision and testing.
The system has flexible and reliable modeling capabilities with high algorithms and a special database concept.

The software offers a complete suite of functions for studying large networks and power systems with multi phasing technologies including single-wire earth return, two-phase system, and the traditional three-phase systems. it provides a comprehensive modeling specification and features for different kinds of electrical network studies.

it offers a large set of tools for analyzing the power generation components, besides providing the needed functionality to perform more complicated studies for the integration of the different renewable power generation systems into the trading generation and transmission networks.

3.1.1 Wind turbine generator models

According to the IEC 61400-27-1 a four different type (seven models) are described and are available in Digsilent [33]:

- Type 1a(WTG with asynchronous generator connected directly to the grid)
- Type 1b (WTG with asynchronous generator connected directly to the grid with UVRT pitch control
- Type 2 (WTG with an asynchronous generator with variable rotor resistance directly connected to the grid)
- Type 3a (WTG with doubly fed induction generator(DFIG)
- Type 3b (WTG with doubly fed induction generator(DFIG) with a crowbar.
- Type 4a (WTG connected via full-scale power converter).
- Type 4b (WTG connected through full-scale power covert. with mechanical model).

In wind farm configuration used in the project, the modes 3b for a doubly fed induction generator with a crowbar is used considering that the model is set with a sample parameter and these parameters will be defined as per the project setting (Power rating, voltage levels, reactive power limits and all parameters of the dynamic models).

- **DFIG Models and equivalent circuits:**

As described in chapter 2, the doubly fed induction generator (DFIG) is a rotor -voltage controlled, slip ring induction machine. where the pulse width modulation (PWM) is connected to the slip rings, controls the voltage magnitude and phase angle of the rotor, while also the produced active and reactive power can be controlled.

In *PowerFactory,* there two different models for the DFIG, the first one with an integrated rotor side PWM converter as showmen the figure 3.1 . and the second is without an integrated PWM power converter as shown in figure 3.2. [34]

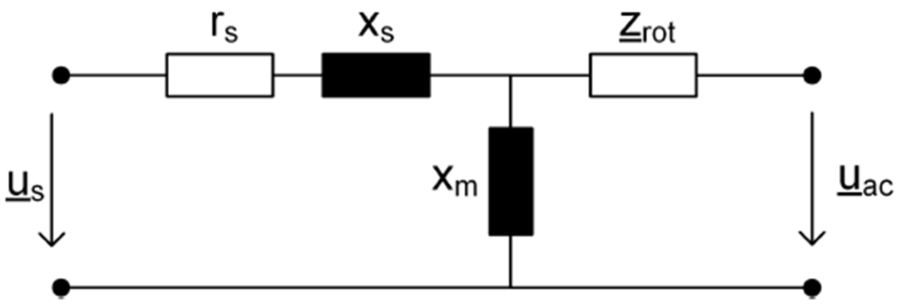

Figure 3.1: DIFG model equivalent circuit without integrated PWM

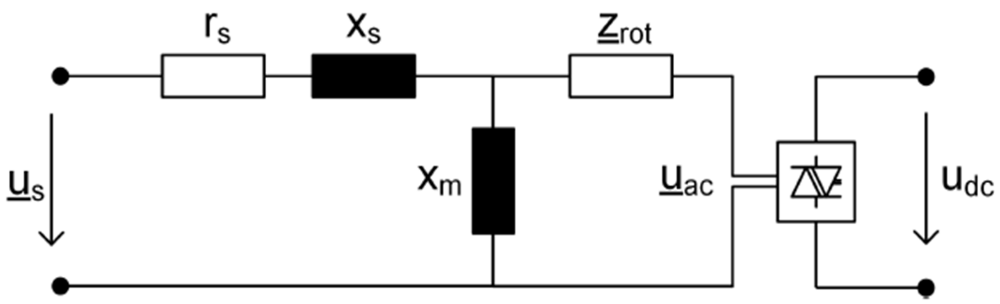

Figure 3.1: DIFG model equivalent circuit with integrated PWM

While the power frequency converter in the rotor side is modeled by a basic frequency approach and the voltages on the DC and AC side are considered related to each other by using the modulation index Pm. figure 3.3 shows the PWM rotor side converter [34].

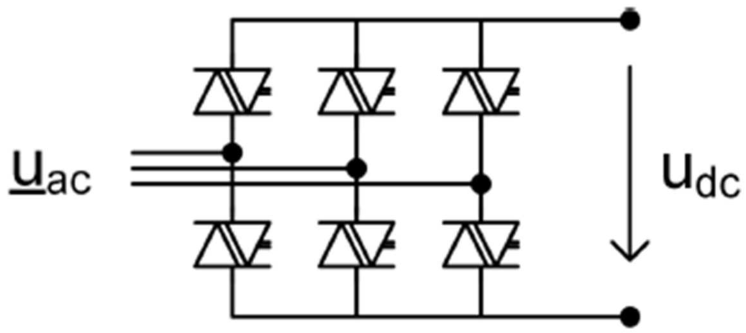

Figure 3.3: PWM rotor side Converter

3.1.2. Three-Winding ´Transformer Model

The three-winding transformer is an element with a three port and connected in the network with three cubicles. the model of the 3_winding transformer in power factor is a built-in model.
For our offshore wind farm project, the transformer type used is a 240 MVA 155 / 33 KV, HV side star connected YN and both MV side are Delta connected.

The model diagrams can be shown for two different types according to the position of the taps.
Positive sequence models with impedance in per unit are illustrated in figure 3.4 and 3.5.[35] the negative sequence models are identical to the positive sequence models.
the winding of the HV, Mv and lv side has a resistance and leakage reactance ($r_{cu,}$ $X_{б}$), the model includes also and iron loss resistance and the magnetization reactance (X_m and r_{fe}), both the iron loss resistance and the magnetization reactance can be modeled in different points, while also the position of the tap can be changed (At star ar at terminal) . [35]

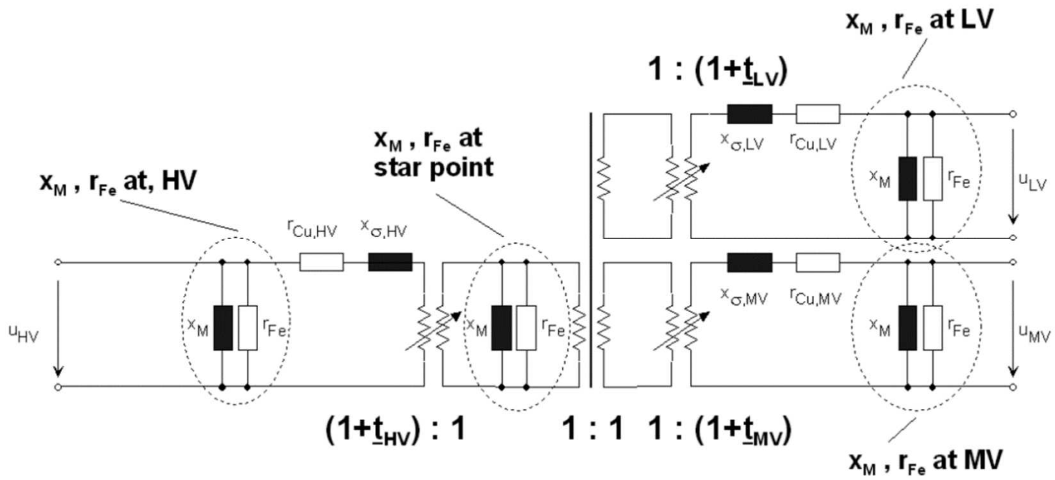

Figure 3.4: Positive-sequence model for Three-winding transformer with taps modeled at the star point (PowerFactory).

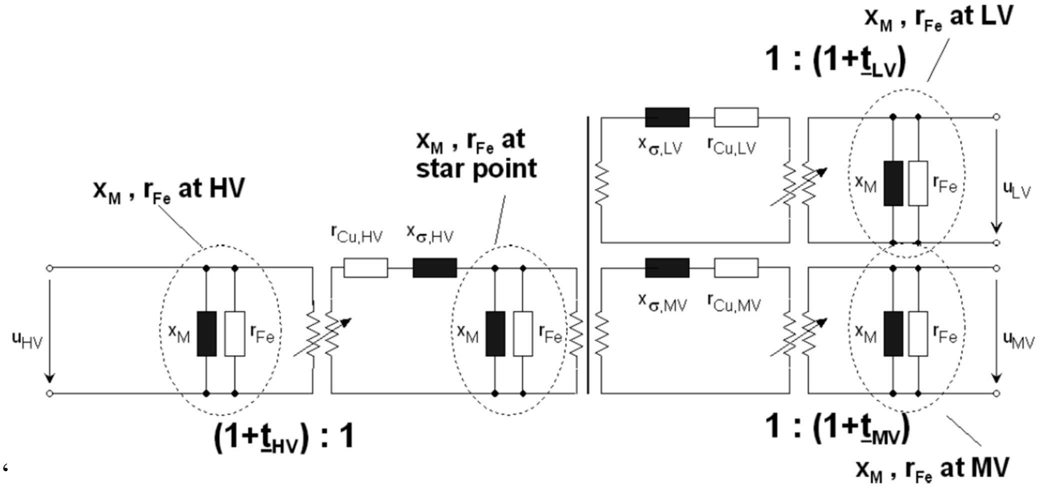

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Figure 3.4: Positive-sequence model for Three-winding transformer with taps modeled at the terminals (PowerFactory).

3.2 Fault analysis for the offshore wind farm

In this part of the project, an offshore wind farm will be constructed and simulated in the Digsilent PowerFactory software.
The detailed construction of the offshore wind farm is discussed, and different cases of fault conditions are analyzed, at the first step the base model of the offshore HVDC wind farm is built by using the software the basic templates of the different farm parts are used from the offshore wind farm model application example in the program with all the preset data and specifications related to the different items in the farm [38]
Simulation of an identified fault in both onshore and offshore are created and the results are discussed, via the simulation the system will show the behavior of the high voltage direct current HVDC system during the case of faults in offshore and onshore sides.

3.2.1 The HVDC Offshore wind farm base model

The HVDC offshore wind farm consists of 80 Turbine wind connected to the high voltage onshore grid through a high voltage DC currents transmission lines (HVDC). The HVDC transmission line is connected to the onshore and offshore via a high voltage source converters (HVDC VSC).

The HVDC transmission lines link a 400 MW offshore wind farm, constructed of doubly fed induction generators (DFIG) for the turbines.

The basic Model of the HVDC offshore wind farm consists of 80 wind turbines, each turbine is equipped with a doubly-fed induction generator (DFIG wind turbine type 3) with 5 MW as nominal active power.

A HVDC voltage source converters on both offshore and onshore sides are connected through a 100 km length, 150 KV High voltage DC current transmission line.
The HVDC offshore wind farm is connected to shore via a high voltage AC 380 KV grid.

Figure 3.5 illustrates the single line diagram of the HVDC system as modeled in PowerFactory.

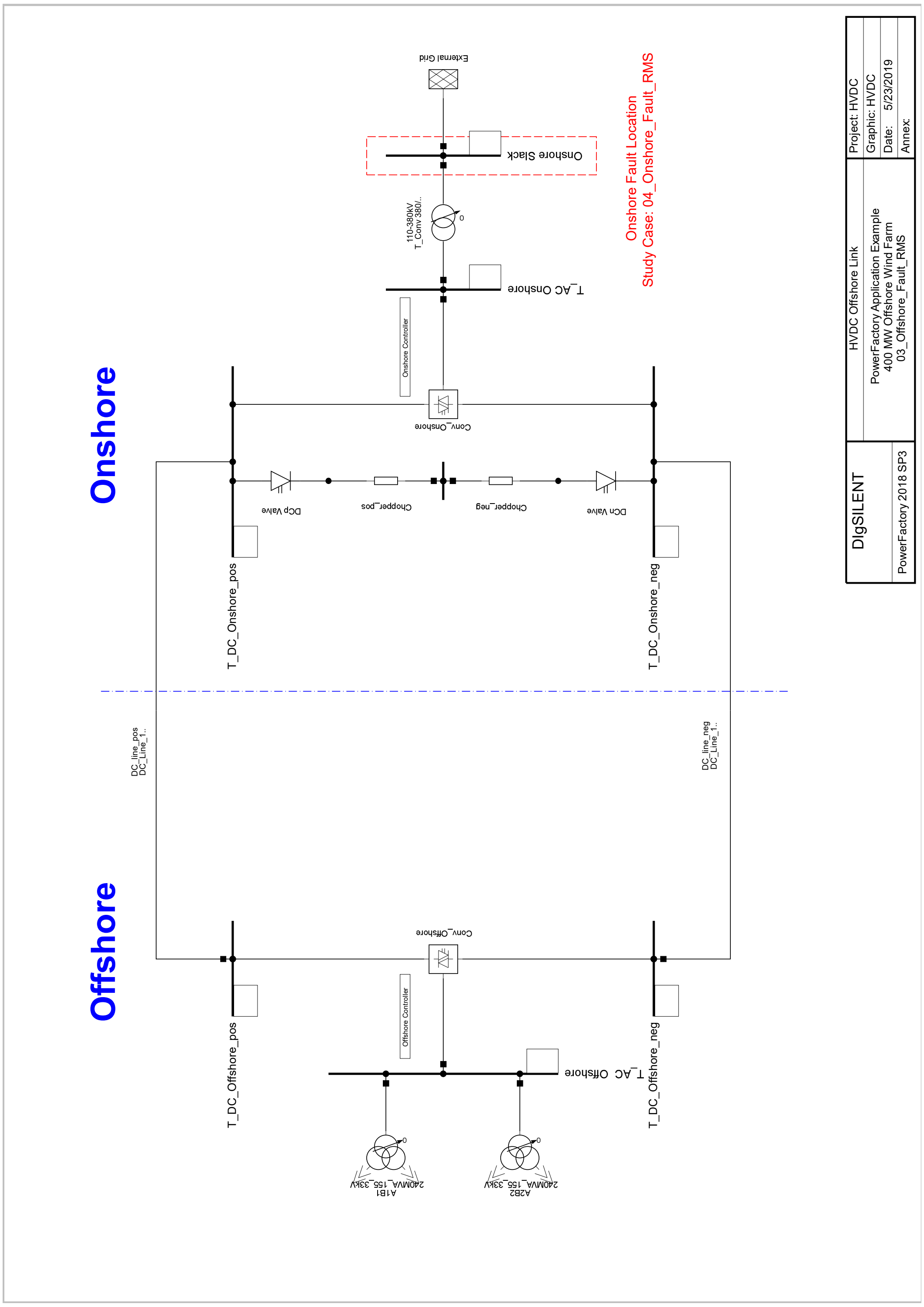

Figure 3.5 Single line diagram for the HVDC System model as per PowerFactory

For the purpose of modeling of the whole offshore wind farm, 10 wind turbines out of the 80 wind turbine are modeled individually.

The detailed singe line diagram illustrates the feeder where the 10 wind turbines are modeled as individual machines.

Figure 3.6 shows the detailed feeder, while to model the rest of 80 turbines, aggregation is used to model the 70 turbines.

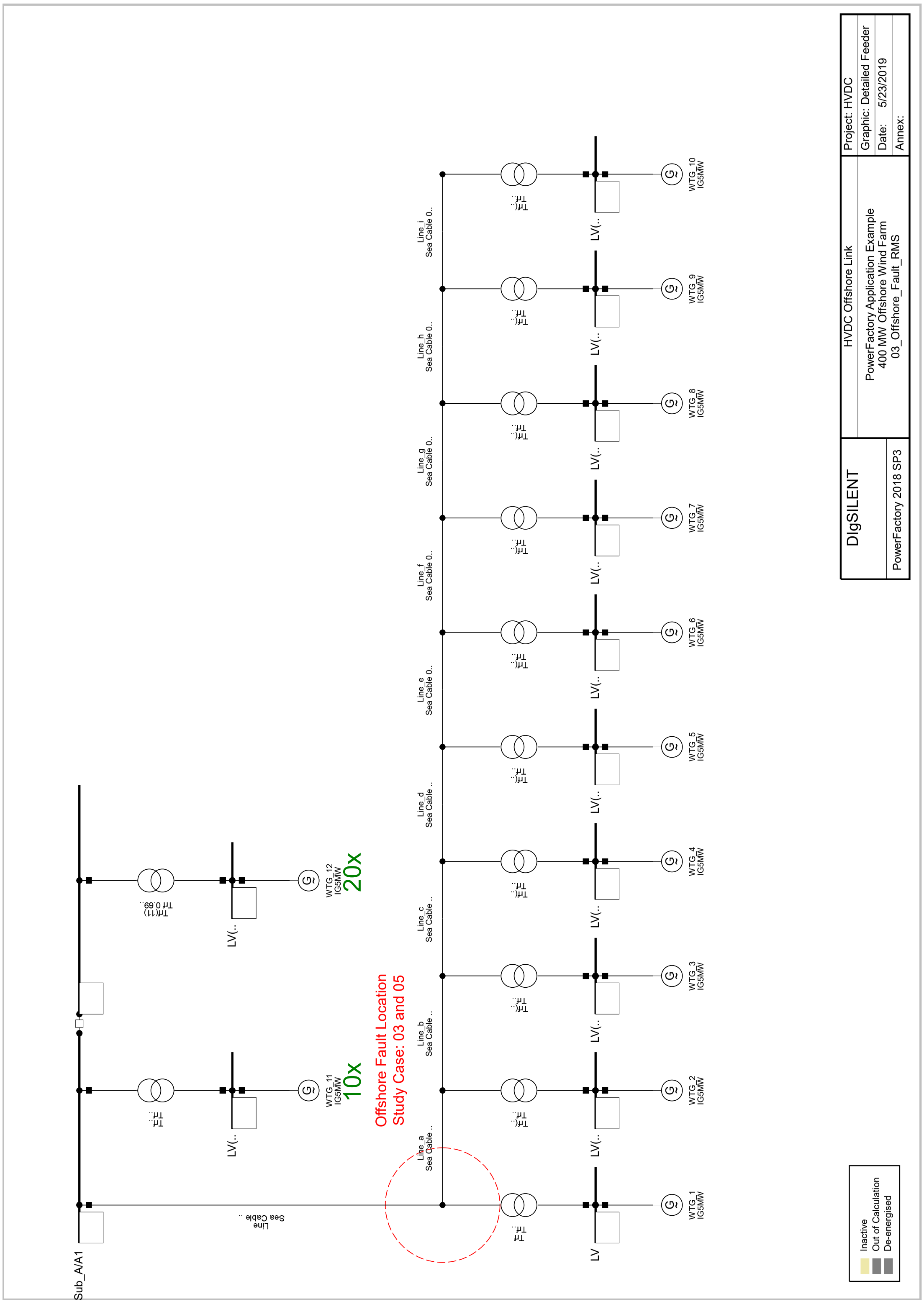

Figure 3.6: Single line diagram for detailed feeder as per Power factory

The remaining 70 wind turbines are modeled in four parts and aggregated in four doubly fed induction generators (DFIG).

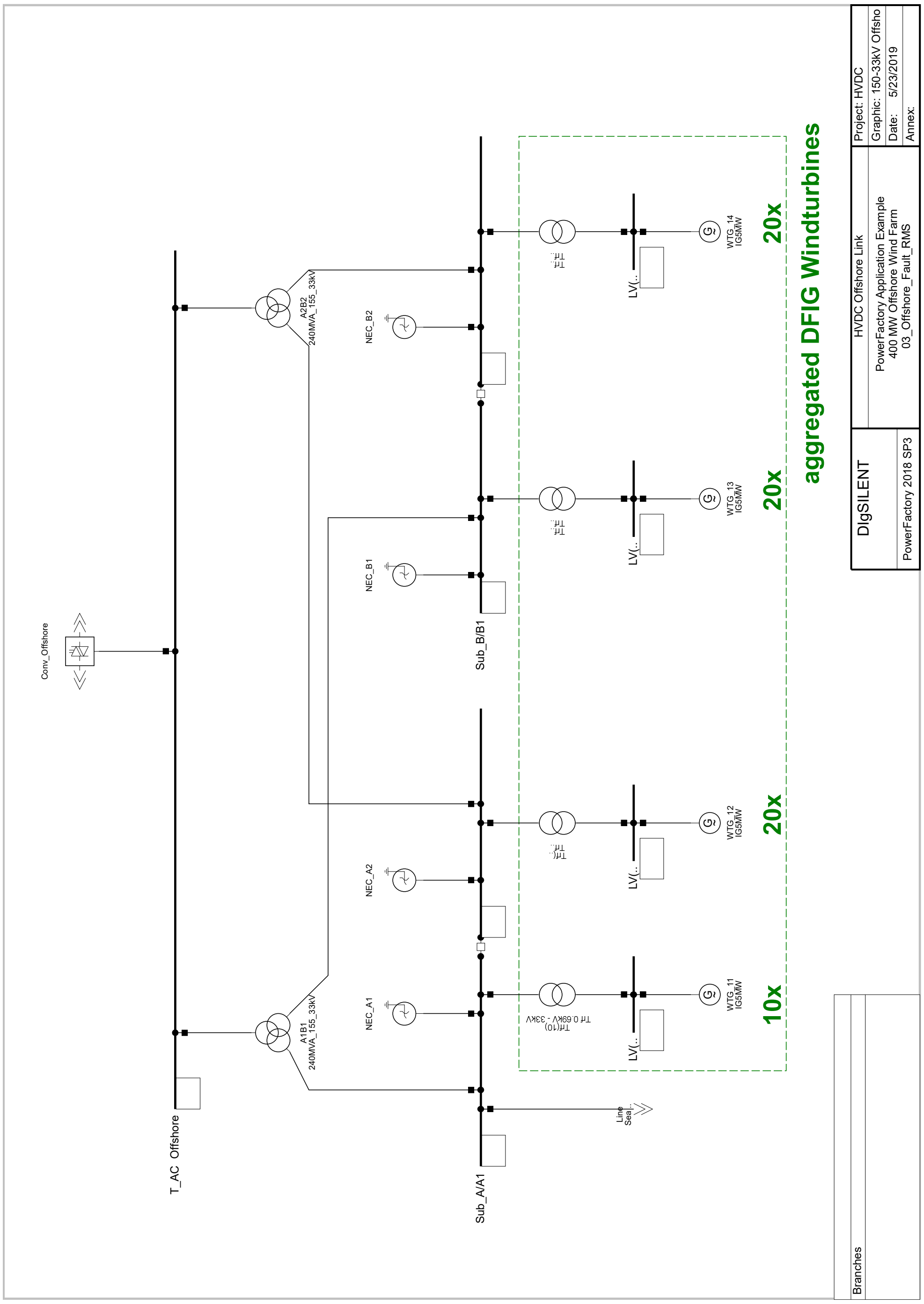

Figure 3.7: the single line diagram model 150-33 Kv offshore - Powerfactory

A three aggregated models will include 20 turbines each, in parallel and one will model the aggregated 10 wind turbines parallel machines
The aggregation concept and model is based on the fact that the wind turbine generator WTG can be used as aggregated representation of-of many wind turbine generators or maybe whole wind farm. the number of parallel WTG or machines, in this case, will be considered in the sending in the basic data page for the element.
while the output active power of the generator will be in this case the number of the parallel machines times the active power dispatch.

The aggregation approach introduces a kind of compromise where a detailed study for the specified model feeder is executed and at the same time, the whole size of the farm is reduced. Basically, the offshore wind farm model in the project has been built using the template of the wind turbine model available in the global library of PowerFactory software.

In this template, the main elements of the wind turbine as a transformer and a generator are modeled and included in the template, besides that, the dynamic models which represent the Phase-locked loop (PLL) and controllers during the RMS and EMS simulations.
Where The phase-locked loop (PLL) for the DFIG is used especially when the voltage of the grid is not balanced, as it realizes the real-time phase synchronization. thus the phase positive sequence components can be obtained accurately and quickly even the grid voltage can be unbalanced [37]

The simulation equations for the frequency converter used on the rotor side is contained in the asynchronous generator model used in the doubly fed induction generator DFIG, so to connect the generator to the network only one connection is needed, that means, the frequency inverter on the rotor side is already included in the connection.
Also, a PowerFactory VSC element is used to model The HVDC transmission line connection link [38].
The used HVDC transmission line Template in PowerFactory for the project, contains all the elements, controllers and all other HVDC types as illustrated in figure 3.5.
The 3- winding transformers are also models by using the template from Digsilent PoweFactory's global library.

3.3 Calculation and Simulations

The model of the offshore wind farm is been built by using the templates for the different elements starting by the wind turbine generator to the the other main elements as the three winding transformers and the HVDC transmission line to the onshore grid including the offshore voltage source frequency converters (VSC) to the step up AC High voltage transformer on the onshore then the connection to the onshore high voltage grid.

A different fault condition is been applied on a different part of the offshore wind farm system, the following sections will discuss and describe the results which can be obtained by using several study cases of faults in the system.
For this purpose and be able to run a time domain simulation for the fault case in the offshore and onshore, the RMS/EMS toolbox in the power factor software should be selected.

The simulations will be visible as results after running and execute the faults on the identified faults locations. the effect on the faulty elements and also the healthy part will be also discussed and analyzed.
According to that different Study, cases will be described and discussed in the following sections

3.3.1 Case 02 Short circuit calculation of the HVDC wind farm

In the case, the short circuit is applied to two locations on the onshore side as illustrated in figure 3.8, where the short circuit calculation is presented on the offshore wind farm.

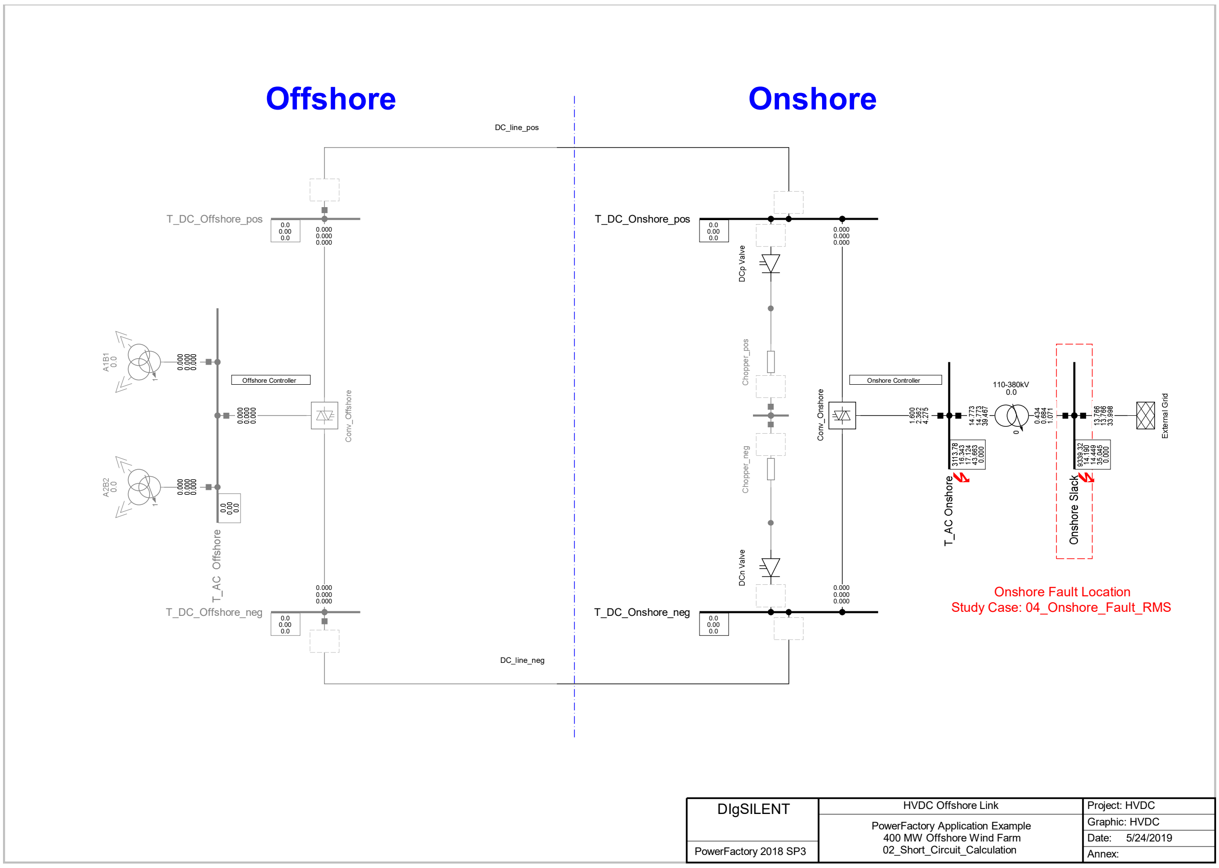

Figure 3.8 Case 02 Short circuit calculation executed on T_AC onshore and Onshore Slack

The short circuit calculated at Terminal HVDC\ Onshore slack and at the terminal HVDC\T_AC on shore with a breaking time 100 ms and fault clearing time 1 s.
The fault type is 3-phase short circuit, the calculation is for max. short circuit currents.
For this situation, the DigSilent Complete method is used to reflect the behavior of the modern wind turbine under fault condition as the IEC 60909 does not support the fault behavior of the modern turbines and this method is used to calculate the contribution of their short circuit.
The short circuit currents I"k, Ib and Ith and others which express the stress on the grid:

S"K: the short circuit capacity in MVA

I"k: Sub-transient short circuit current in KA
I'K: transient short circuit current In KA
Ib: short circuit breaking current in KA

I_{th}: Thermal equivalent short circuit current
ip: Peak short circuit current in KA
The currents Ib and Ith are calculated on the basis of I"k and I'K
on figure 3.9, the detailed values of the max short circuit current on the identified location are illustrated

```
short circuit calculation results - Notepad
File Edit Format View Help
info - Element 'External Grid' is local reference in separated area of 'Onshore Slack'
info - Grid split into 9 isolated areas
info - Short-circuit calculated at Terminal HVDC\Onshore Slack
info - Short-circuit calculated at Terminal HVDC\T_AC Onshore
info - Short-circuit calculation successfully executed!
-----------------------------------------------------------------------------------------------------------------------------
|                |                                                            |  DIgSILENT   | Project:                     |
|                |                                                            | PowerFactory |------------------------------|
|                |                                                            |   2018 SP3   | Date:  5/24/2019             |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Fault Locations with Feeders                                                                                               |
| Short-Circuit Calculation / Method : complete                            3-Phase Short-Circuit    / Max. Short-Circuit Currents |
-----------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                  | Fault Impedance                           |                                      |
|    Break Time                   0.10 s  |    Resistance, Rf               0.00 Ohm  |                                      |
|    Fault Clearing Time (Ith)    1.00 s  |    Reactance, Xf                0.00 Ohm  |                                      |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Grid: HVDC                  System Stage: HVDC              |                                     | Annex:            / 1      |
-----------------------------------------------------------------------------------------------------------------------------
|                     rtd.V.    Voltage     c-        Sk"            Ik"              Ik'          ip       Ib      ib     Ith |
|                     [kV]    [kV]   [deg] Factor    [MVA]        [kA]    [deg]    [kA]  [deg]    [kA]     [kA]    [kA]    [kA]|
-----------------------------------------------------------------------------------------------------------------------------
|                                                                                                                            |
|Onshore Slack       380.00    0.00    0.00  1.00   9339.32 MVA  14.19 kA  -86.4   14.45  -86.6   35.04 kA  14.43   21.28  14.43 |
|    110-380kV        T_AC Onsho                     285.44 MVA   0.43 kA  105.8    0.68   95.4    1.07 kA                      |
|    External Grid                                  9060.49 MVA  13.77 kA  -86.7   13.77  -86.7   34.00 kA                      |
|                                                                                                                            |
|T_AC Onshore        110.00    0.00    0.00  1.00   3113.78 MVA  16.34 kA  120.7   17.12  120.3   43.66 kA  17.06   31.48  17.02 |
|    110-380kV        Onshore Sl                    2814.57 MVA  14.77 kA  -60.5   14.77  -60.5   39.47 kA                      |
|    Conv_Onshore     T_DC_Onsho  T_DC_Onsho          304.84 MVA   1.60 kA  131.1    2.36  125.4    4.27 kA                      |
-----------------------------------------------------------------------------------------------------------------------------
Exported graphic to: C:\Mater Degree\Master 2017\2019\Project\Templates\Prints\short circuit calculation.emf
```

Figure3.9 Shows the results of the short circuit calculations (as values)with a short circuit in two locations.

The results show the maximum short circuit currents in the targeted locations, and by using this information, the designed short circuit capacities of the system elements can be defined, then the installed short circuits protection devices such as short circuit protection relays, circuit breakers beside that the short circuit capacities of the installed elements can be evaluated such as transformers and other parts.

3.3.2 Case 03 the fault is on Offshore RMS

Fault Located atTerm_b

The short circuit in the offshore part of the offshore wind farm system is discussed and analyzed. the fault location will be in the feeders of the offshore part and the for this case the fault is in terminal-b (First node) as figure 3.10 shows the feeder location and the faulted terminal.

The fault is also discussed in other terminal points (Third node) and (sixth nod) in the offshore feeders. by executing the fault at a different point (Feeders) the effect and consequences on the healthy part of the network can be evaluated.

To study the fault case, the RMS simulation method is used, where the fault is executed and identified by first define “Results for Simulation RMS/EMS” so we can also define the variables we need to monitor during the fault condition, then by define “short Circuit fault event” at the fault location point (Terminal-b this case), here.

The time for start the fault event is set and also the fault type (Single phase, 3-phases,..etc).

For this case, Fault starts at terminal-b at 0.0 s and continued for 200 ms until it's cleared by opening the protection facility (circuit breaker) connects the related faulted point to the Sub-A/A terminal.

Figure 3.10 (a, b, c) shows the faulted feeders and the fault location point, also illustrate the active and inactive elements besides the loading range by colors on the different offshore wind farm parts, during and after the fault cleared:

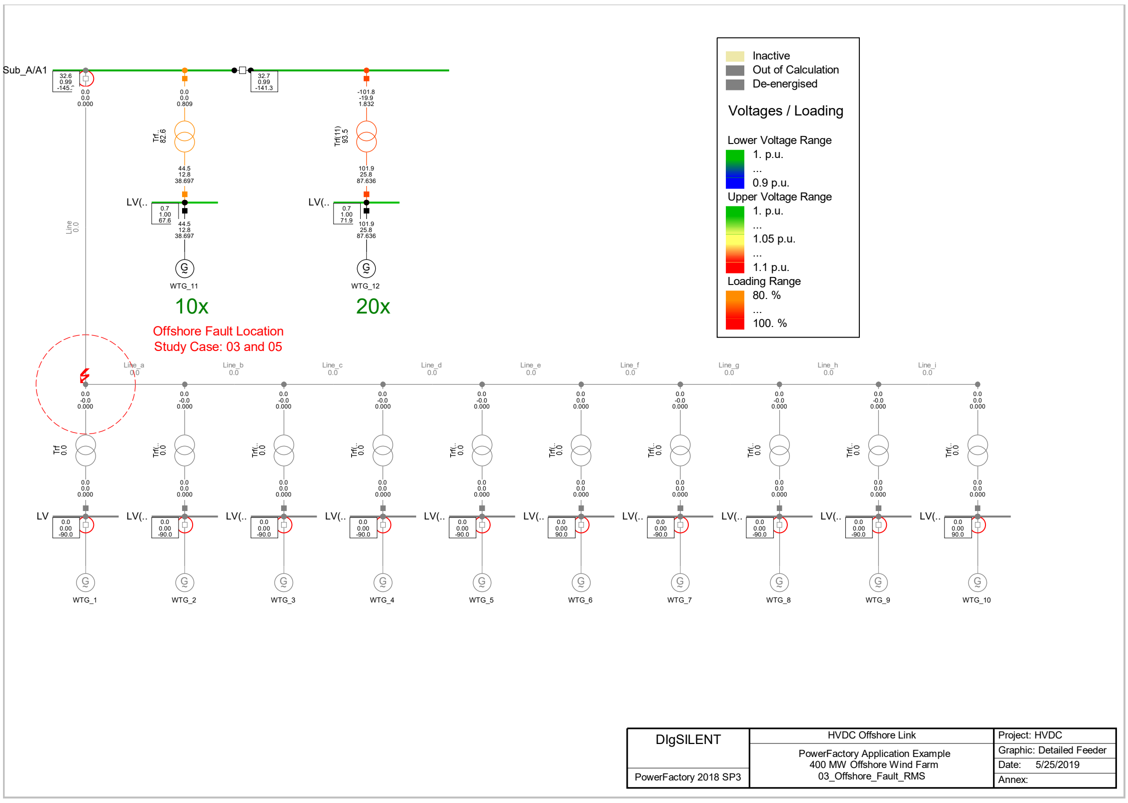

Figure 3.10a: Fault on terminal-b on the detailed feeder

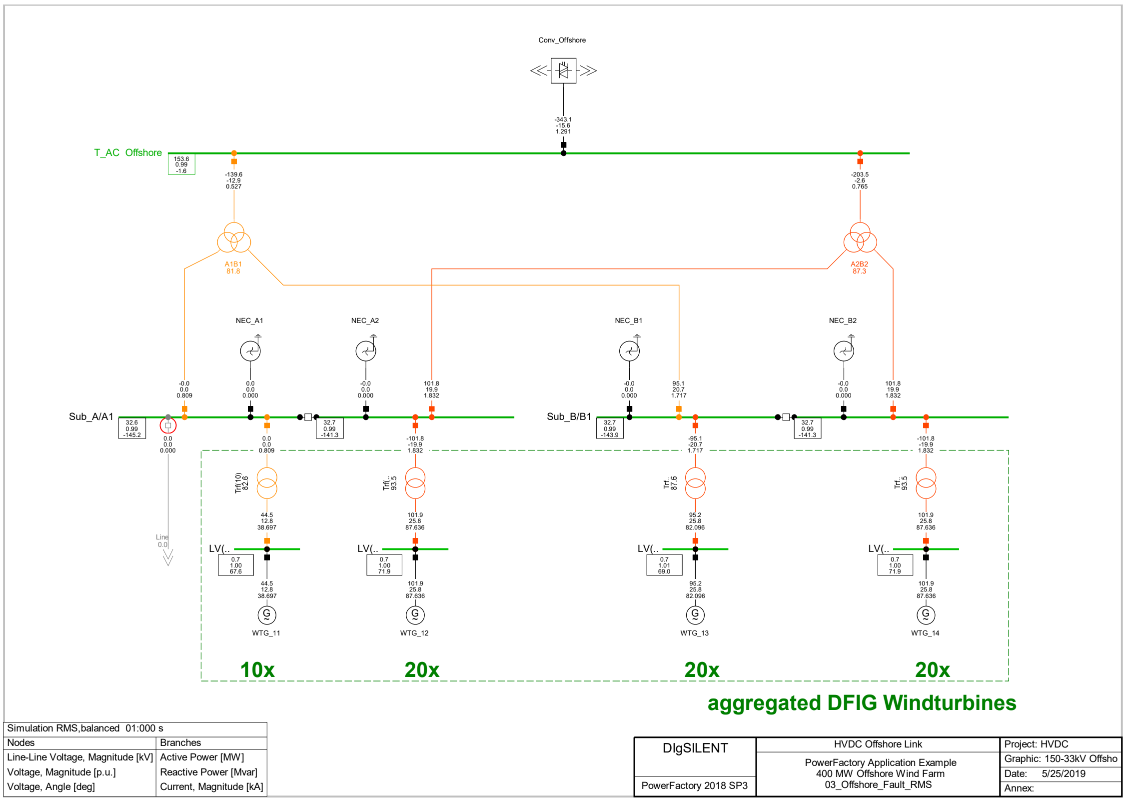

Figure 3.10b: : 150/33 KV offshore station (Fualt on feeder terminal-b)

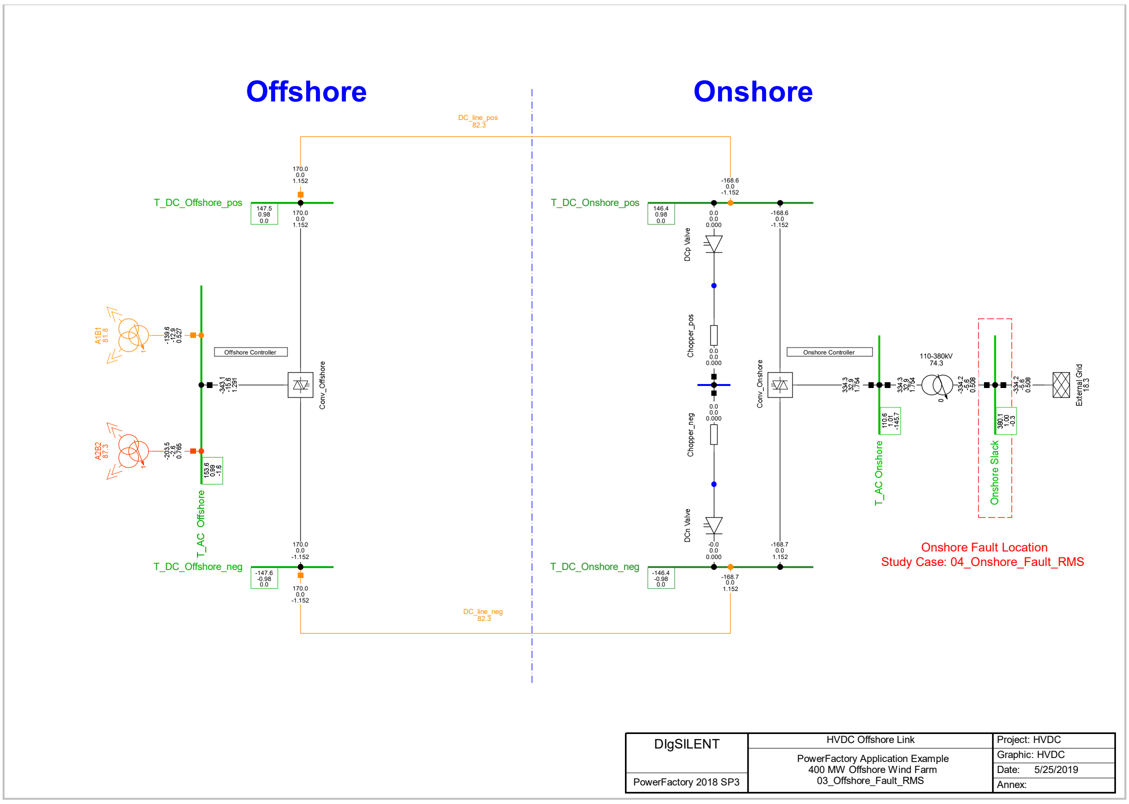

Figure 3.10c: HVDC (Fault on feeder terminal-b)

The three figures show by colors the active and inactive parts.

The results can be presented and plot by two (VI) virtual instruments, the two panels are (Windpark-SIM and HVDC -SIM).
The virtual instrument (HVDC-SIM) reflects the results of the two HVDC terminals, the virtual instrument VI (Windpoark-SIM) reflects the results for the wind turbines and the fault current.
figure 3.11 and 3.12 shows the detailed diagram of the system behavior under a fault condition in the offshore part located in terminal_b.
Under the fault condition, the results for the faulted part in terminal_b, the sub-A/A1 busbar and the healthy terminals voltages for the HVDC are illustrated.

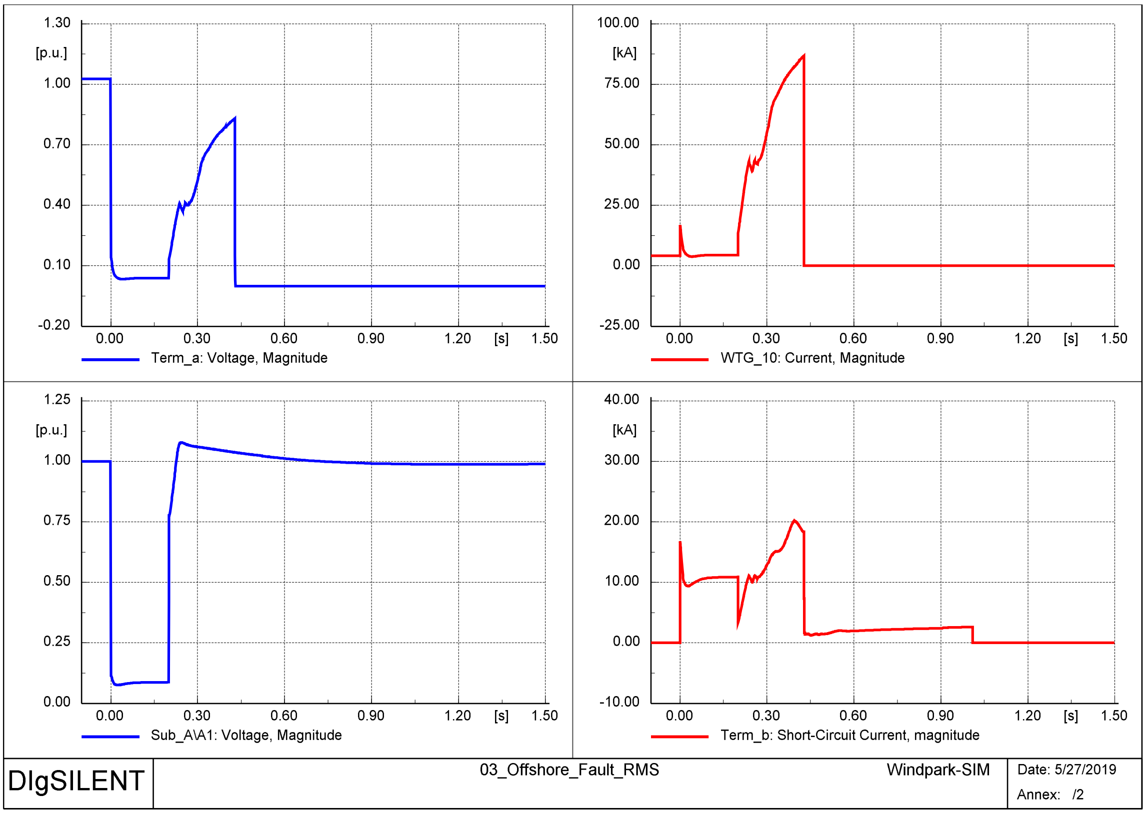

figure 3.11 Windpark-SIM results of the offshore fault at Terminal_b, RMS simulation

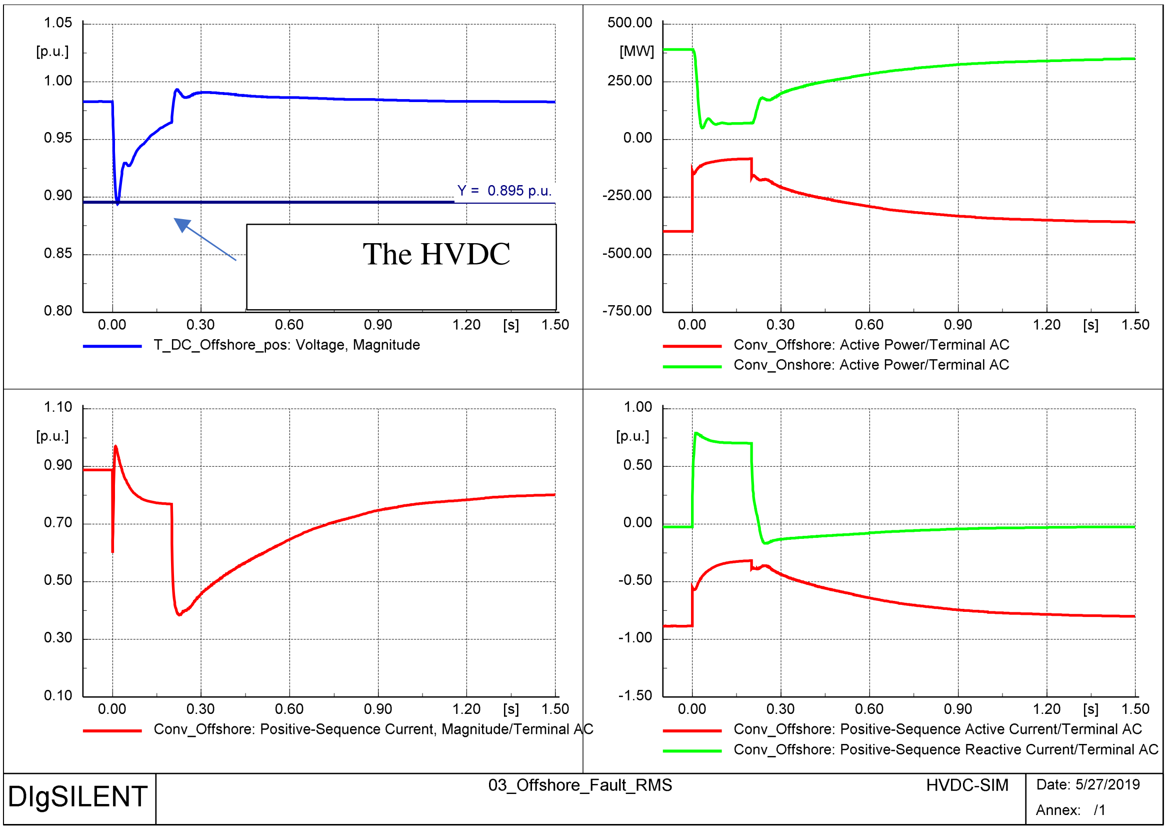

Figure 3.12 HVDC-SIM Result offshore fault at terminal _b RMS simulation

The results show the short circuit fault in the offshore part of the system can be handled without the need to trip or isolate the HVDC high voltage direct current transmission lines, this can be explained as the fault occurred in the 33 kV part of the network didn't lead to a high voltage drop on the terminals of HVDC transmission lines.
Figure 3.12 shows results (from the virtual instrument VI HVDC_res) of the drop in voltage in the HVDC which is less than 0.8 pu and that is referred to the impedance of the 3-winding transformers.
The behavior of the converter on offshore also detected under the fault period to retain its normal operation gradually after the faulted feeder is disconnected and also fro the converter active and reactive power affected by the fault and moving to the "0" value, but to come back also gradually to its normal values after the faulted feeder is disconnected, this behavior is controlled by the controllers of the onshore and offshore converters.
The behavior of the system under the fault condition in terminal_b location can be discussed and explained.
As illustrated in figure 3.13 The doubly fed induction generator DFIG wind turbine in the detailed faulted feeder continues to supply a short circuit fault current to the fault location terminal _b even after the feeder is disconnected after the tripping time of the related circuit breaker (200 ms), where the turbines are disconnected by the protection system scheme at the end.

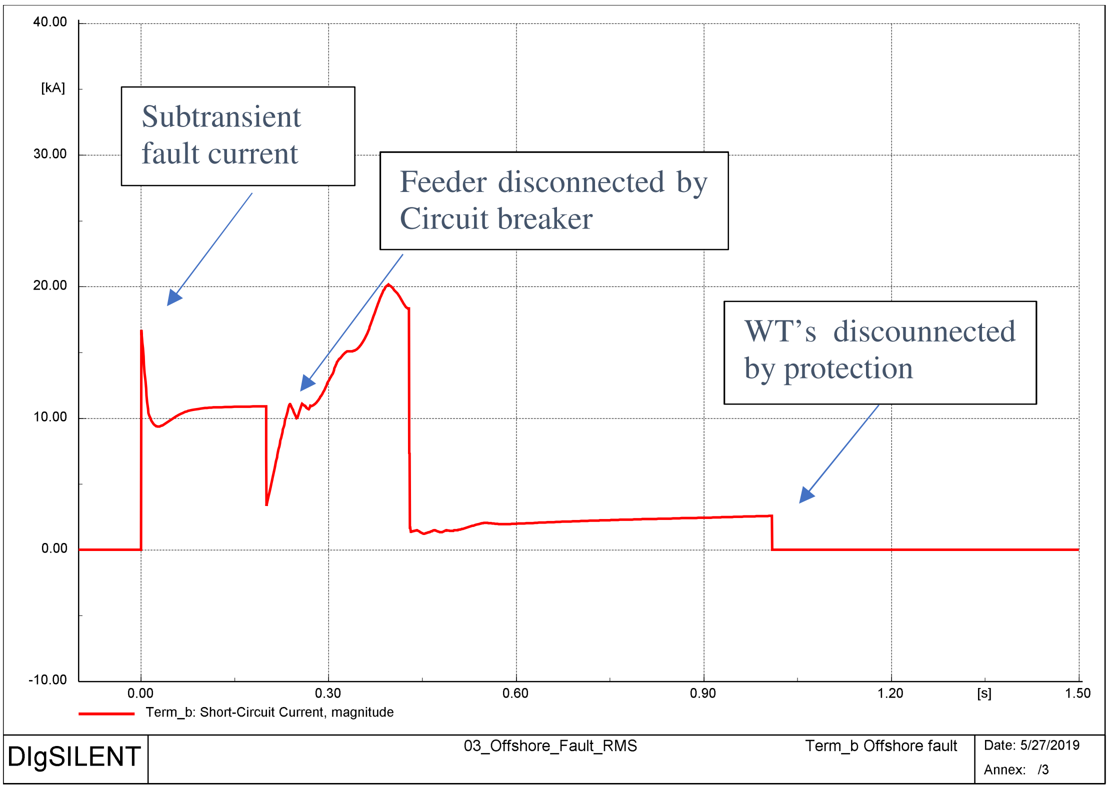

Figure 3.13 Windpark-SIM offshore fault Terminal_b RMS simulation

Another case study with a fault can be executed on another location on the detailed feeder.

- **Fault located in Terminal ”g”:**

  In this case, a short circuit event of three-phase short event executed at terminal_g. the event starts at the time (0), with a short circuit period of 300 ms.
  The single line diagram shows that the short circuit did not lead to open the feeder circuit breaker while all the protection circuit breakers for the turbine 6 to 10 is tripped and isolate the related turbines.
  The detailed feeder connection with Sub_A/A circuit breaker remains closed and does not affect by the fault.
  while the fault on this location also did not lead to trip the main HVDC transmission lines, and the voltage on the HVDC terminal did not droop less than 0.8 pu, which is also can be explained by the three winding transformers impedance.
  figure 3.14 shows the single line diagram of the detailed feeder under fault in Terminal “g” and the HVDC terminal voltage with a red circle on the isolated turbines (6-10).

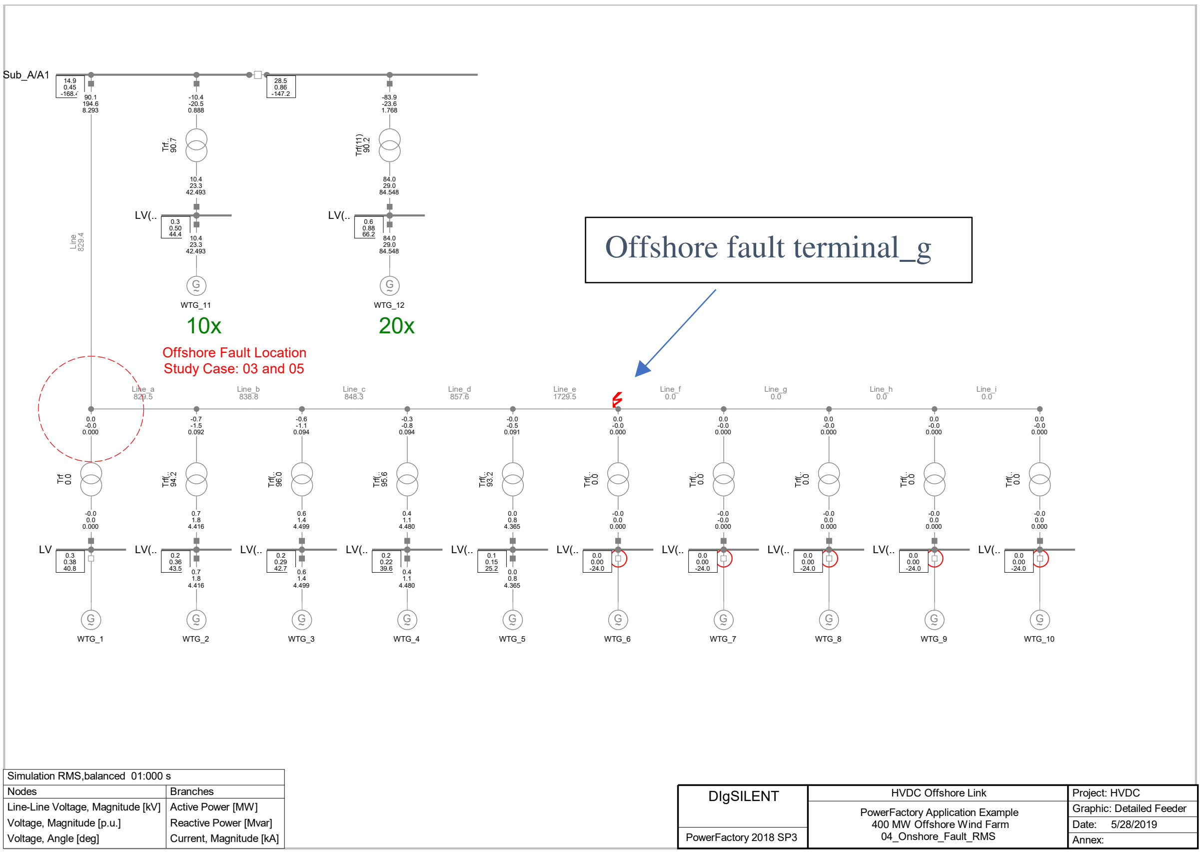

Figure 3.14: Single line diagram - Fault on offshore detailed feeder terminal _g

Also, figure 3.15 shows the drop in the HVDC terminal voltage under the fault condition in terminal_g.

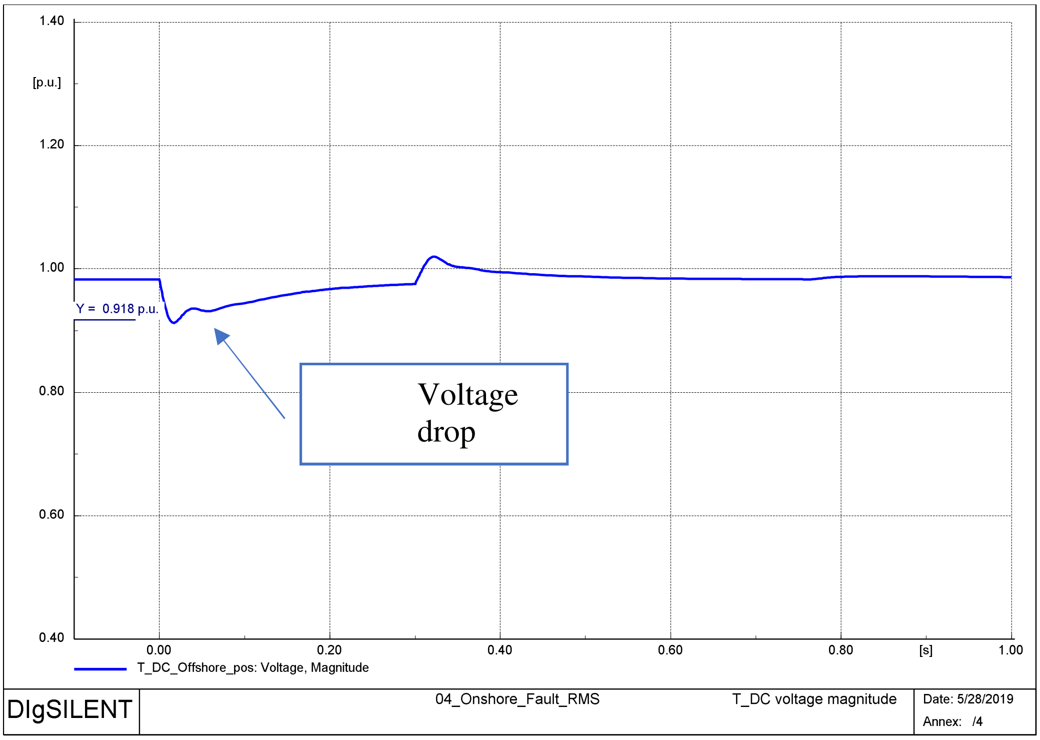

Figure 3.15 HVDC Voltage magnitude- Offshore fault Terminal_g RMS simulation

The short circuit current at the fault location terminal-g can be shown in figure 3.16 where the behavior is similar to the short circuit current in Terminla_b, while no simulation for the feeder disconnection as the feeder remains supplied by the other turbines(1-5).

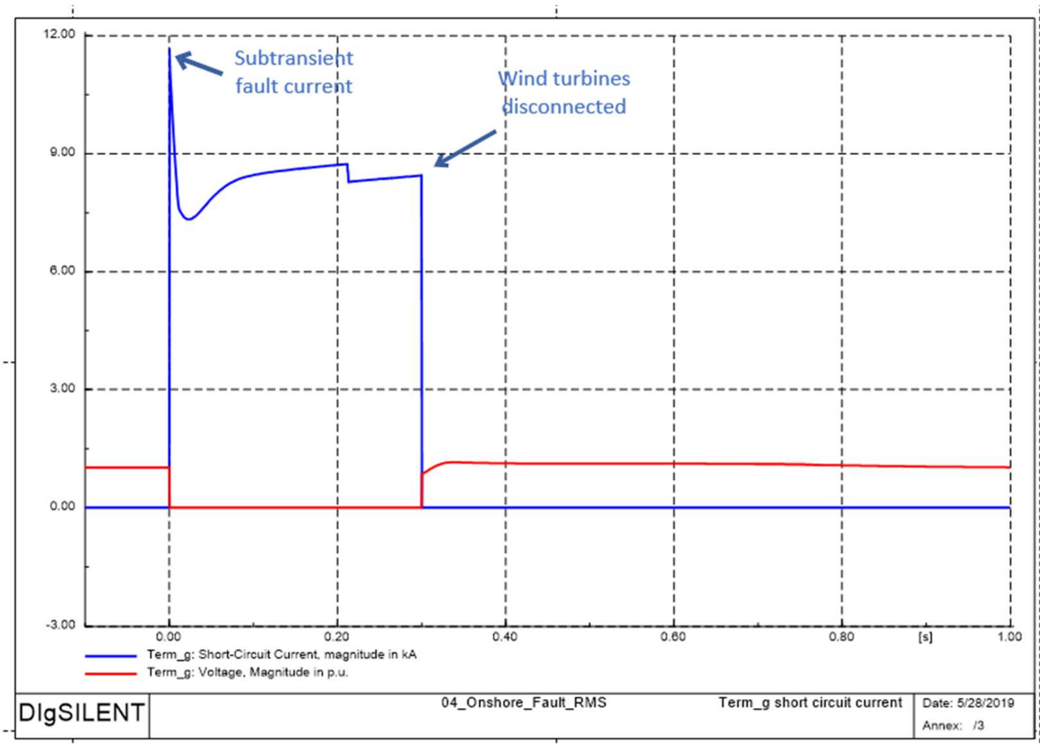

Figure 3.16 Offshore fault short circuit current Term_g – RMS simulation

3.3.3 Case 04 Onshore Fault RMS

The short circuit in the onshore part of the offshore wind farm system is discussed and analyzed in this section and the fault is located in the “Onshore Slack”.
As per the previous case, the RMS simulation method will be applied and a short circuit condition in the onshore slacks is presented and discussed.

As per Digsilent power, factory to simulate the fault in the onshore Slack, the starting point is to define the simulation in RMS. then use the short circuit event to have the fault defined at the fault location.
In DigSilent power factory the fault event is executed with one event and the clearing the fault is achieved via the second event.
in this section, the fault event executed in time ”0” sec and the period of fault event is considered 200 ms until the fault event.
the goal to see the consequences of short circuit fault event at the onshore slack on the other healthy part of the electrical system of the offshore wind farm, especially to understand how the onshore converter and the offshore converters behave during the fault condition and after the fault is cleared.
The high voltage DC on the output of the offshore converter side (T-DC offshore converter) is to be monitored and checked relating to the fact that during the fault even, no active power is transmitted to the other side while the farm could remain at operation and producing stage.
Two virtual simulation instrument is used, HVDC-SIM and WindPark-SIM, the HVDC-SIM is used to illustrate the results of the two HVDC transmission line terminals, while WindPark-Sim is used to represent the results of fault current the wind turbine.
Figure 3.17 shows the offshore wind farm during a fault event at the onshore Slack, with clearing the fault.
Figure 3.18 also illustrates the behavior of the system during the fault event condition without clearing the fault.

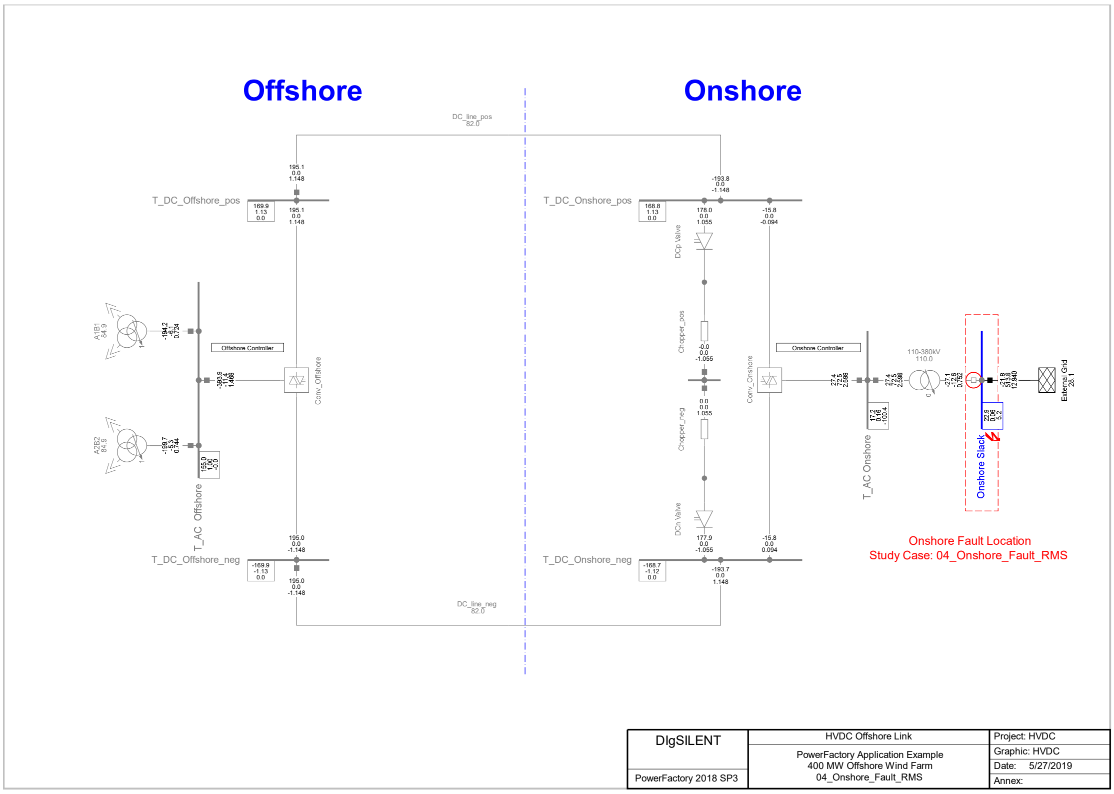

Figure 3.17: SLD of the HVDC part during an uncleared fault on Onshore Slack

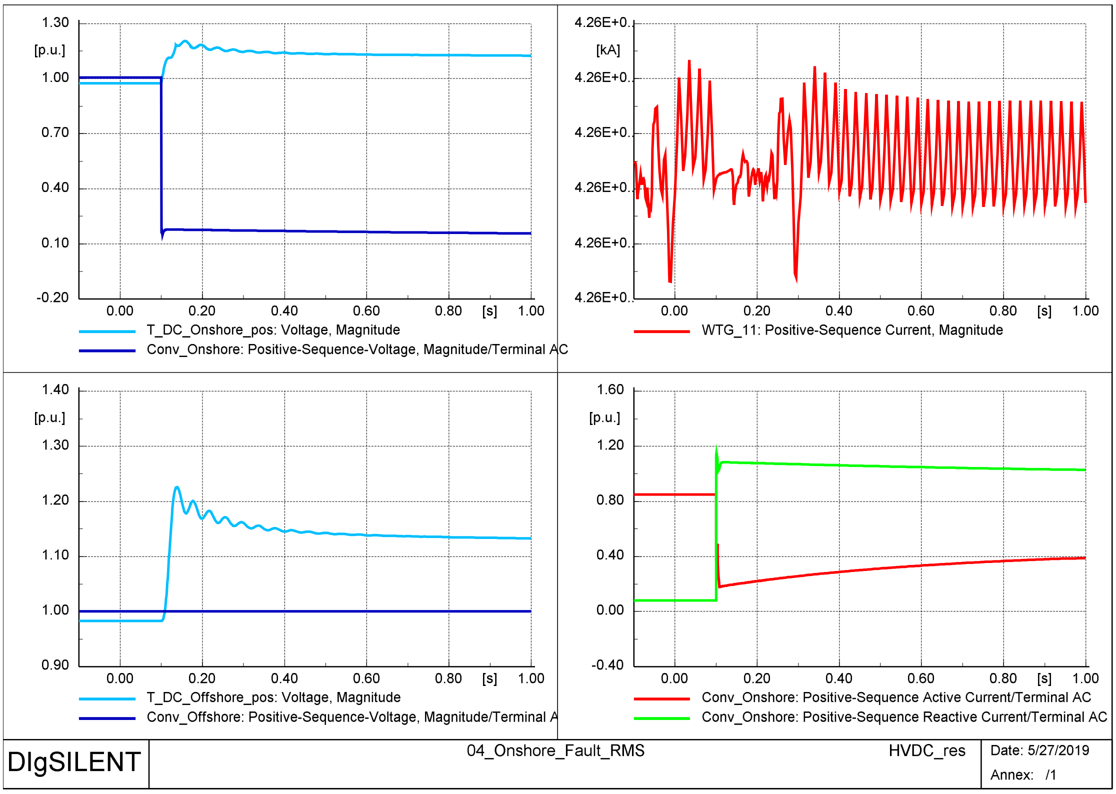

Figure 3.18: HVDC behavior during an uncleared fault (1 sec)on the Onshore slack

The second part of the case the fault is cleared after 200 ms and the diagrams in figure 3.19 show the behavior of the HVDC offshore and onshore terminals and figure 3.20 illustrate the effect of the onshore fault slack on the wind turbines on offshore.

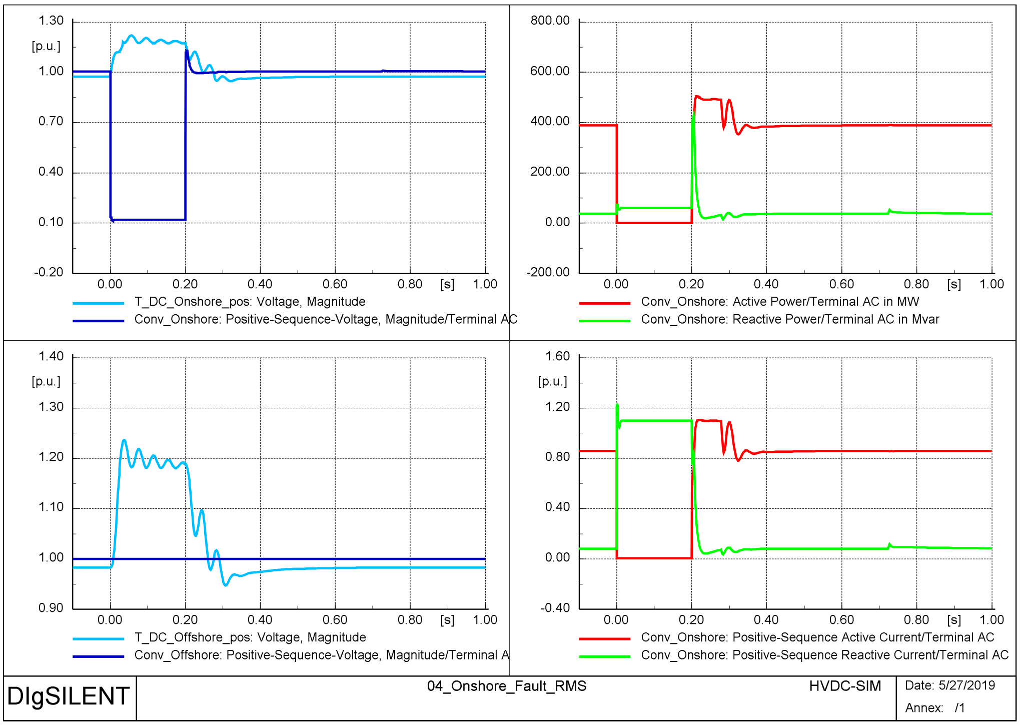

Figure 3.19: HVDC terminals during a fault (cleared after 200 ms) Onshore slack

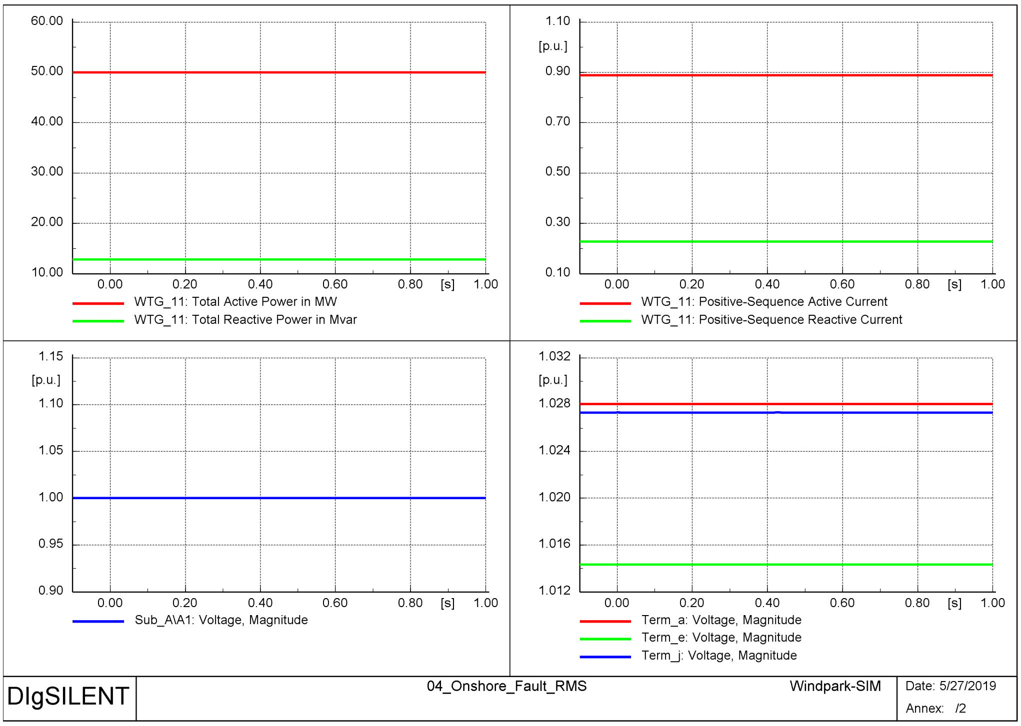

Figure 3.20 The wind farm during onshore fault Slack - RMS simulation

As per the diagrams on figure 3.20, the presented results for the onshore fault Slack shows that the wind farm is not affected by the fault, this can be explained by the existence of the

HVDC transmission lines which link the offshore part of the system to the onshore, thus its decouples the fault event effects on the offshore wind turbines and offshore station.
On the other side and during the fault condition, where the active power is not transferred from the wind park to the onshore side and the external grid, the produced active power which cannot be transmitted to the grid will be discharged and consumed by the chopper resistors as figure 3.21 illustrates.
The onshore Chopper control concept is built on the way that it has an input signal from the HVDC Positive and negative terminals. by using these signal the controller can limit the HVDC over voltage especially in case of an onshore fault, by igniting the DC valves of the chopper resistors in case the voltage increased over a certain limit. In case of an onshore fault, the power can't be transmitted to the AC network through the converter and results in a high charging of the DC circuit, which can lead to serious damages in the IGBT of the converter.
The chopper will block the valves again when the voltage drops again under the specified threshold.

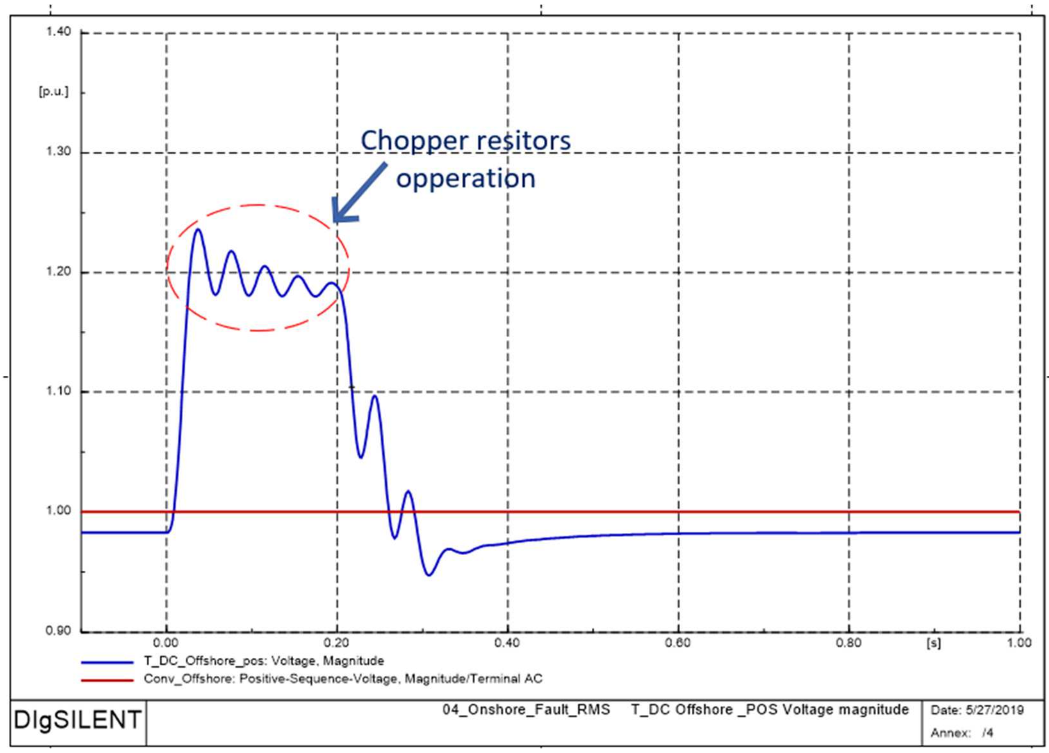

figure 3.21 T-DC Onshore fault Slack (Voltage magnitude) Chopper action

On the onshore part, where there is no grid connection during the offshore slack fault, the onshore converter(Conv_offshore) changes its mood to reactive current priority, thus the controller for droop voltage and reactive power is allowed to increase the submitted reactive current to a maximum high value.

Figure 3.22 shows the reaction of the Onshore converter during the fault period on the positive sequence active and reactive current on terminal T_AC in pu.

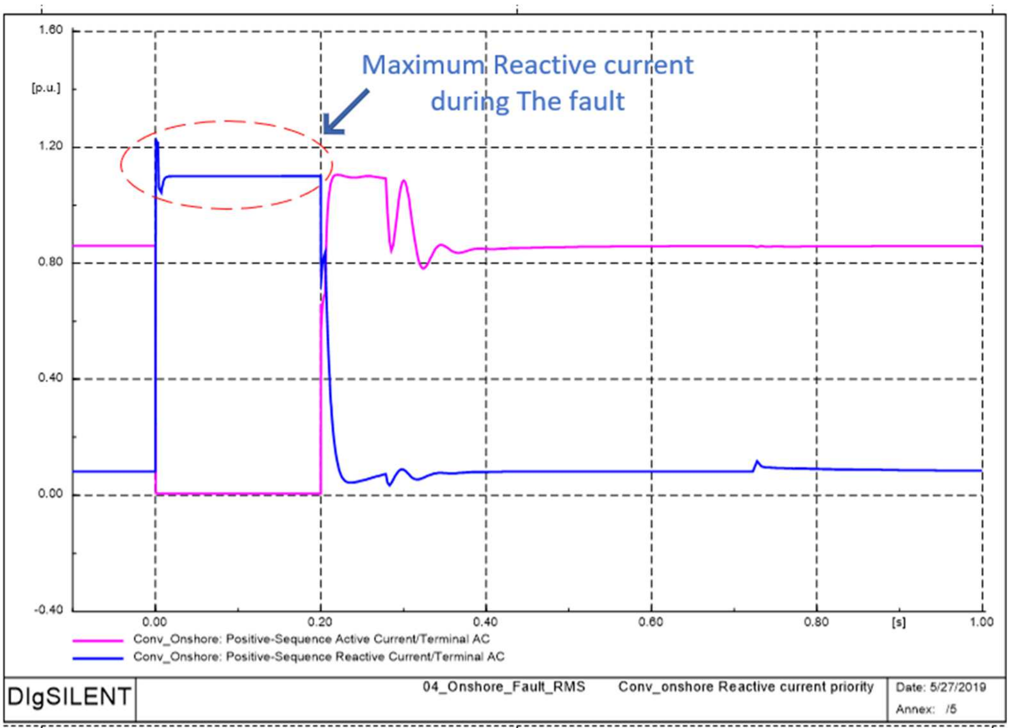

Figure 3.22: Conv_Onshore active and reactive currents during the fault onshore Slacks

The short circuit current on the fault location can be seen in figure 3.23, which illustrate the maximum short circuit current (3-phase) reached under the fault.

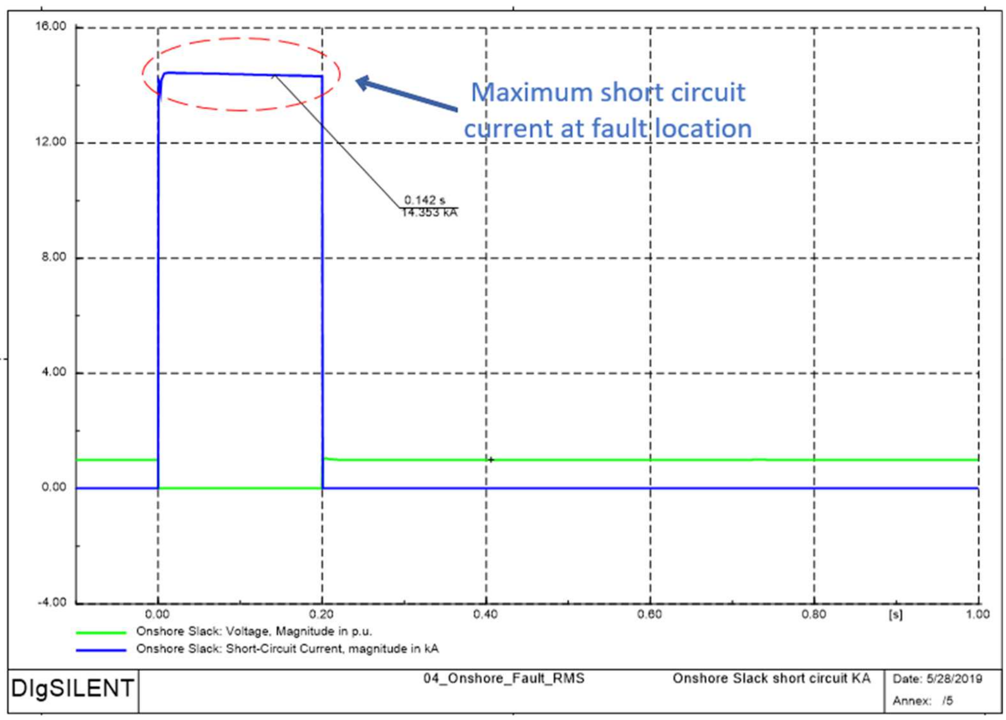

Figure 3.23: Onshore Slack fault short circuit current (RMS simulation)

3.3.4 Case 04 Fault on the HVDC transmission lines

In this part will simulate a fault in the t HVDC transmission line where we can see the level of the short circuit and also the current on the onshore the high voltage transformer side and the offshore three-winding transformer side.
and offshore side in the three wins
Figure 3.24 shows the fault location at 50% of the HVDC transmission line in the single line diagram.

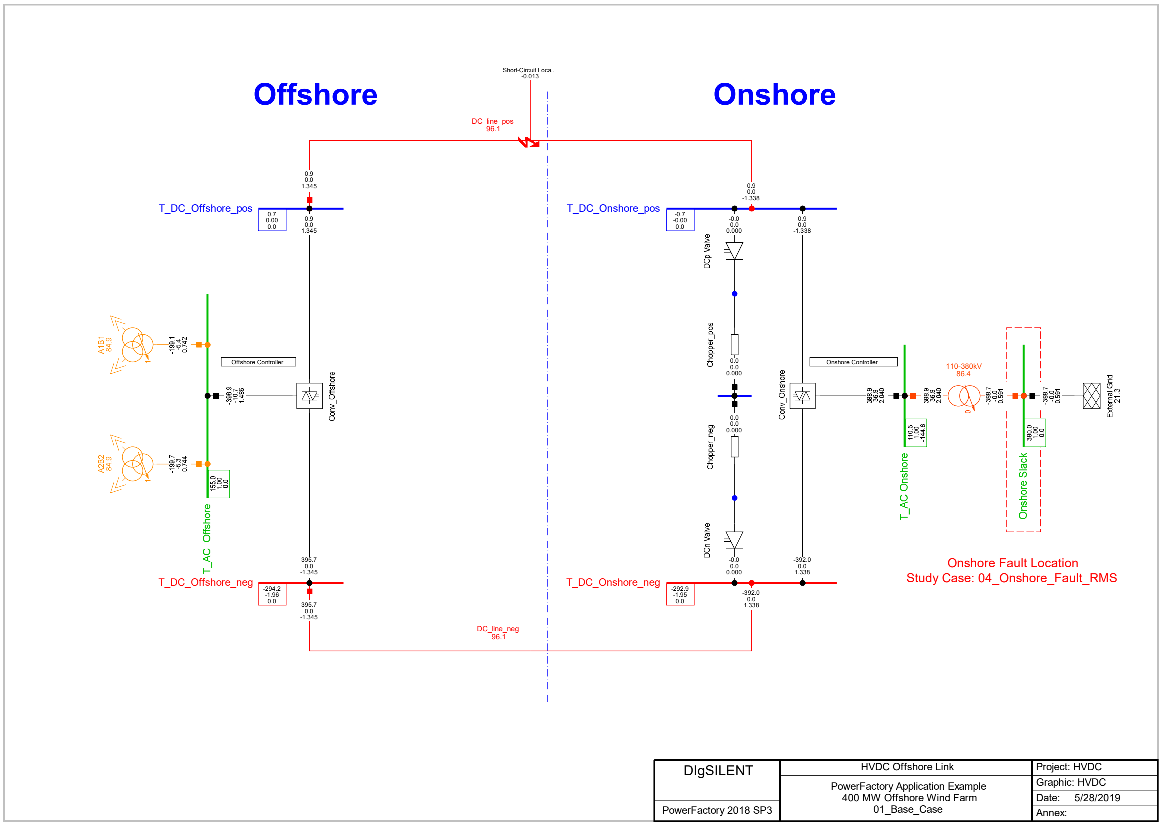

Figure 3.24 HVDC transmission line fault location as per Digsilent PowerFactory

While figure 3.25 shows how is the short circuit current diagram appear during the fault event and what is the maximum short circuit current at the fault location.

The fault occurs on the positive transmission line at a time “2 sec” and cleared with another short circuit even, the fault duration time is 1 sec, the simulation time is 4 sec.

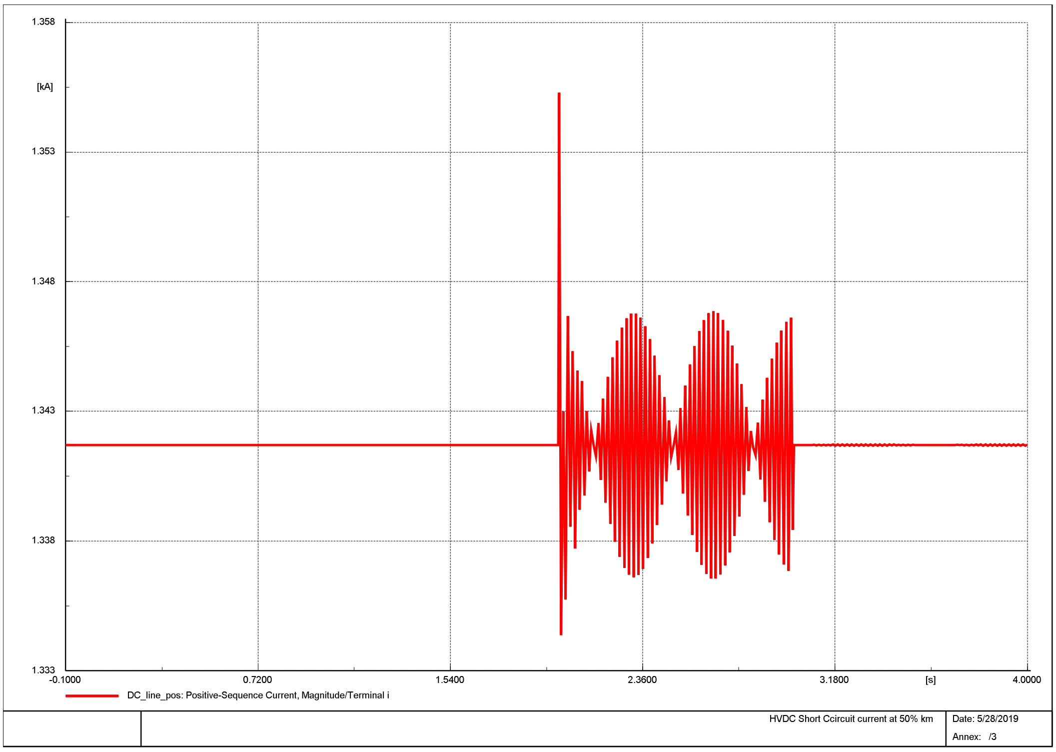

Figure 3.25 HVDC short circuit event at 50 % km - RMS simulation

Also, the current on the offshore side and onshore side can be disused and monitored. Figure 3.26 and 3.27 illustrates how the currents in both sides of the HVDC transmission line change under the fault condition in the line.

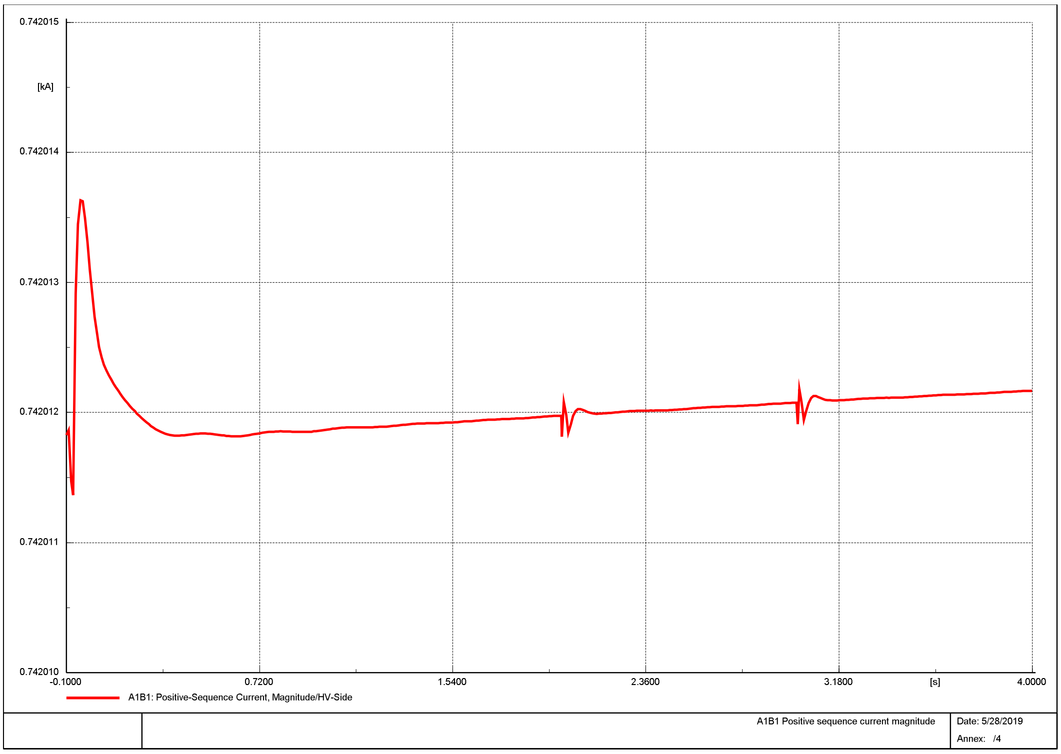

Figure 3.26 A1B1 positive sequence current, Magnitude/ HV sid

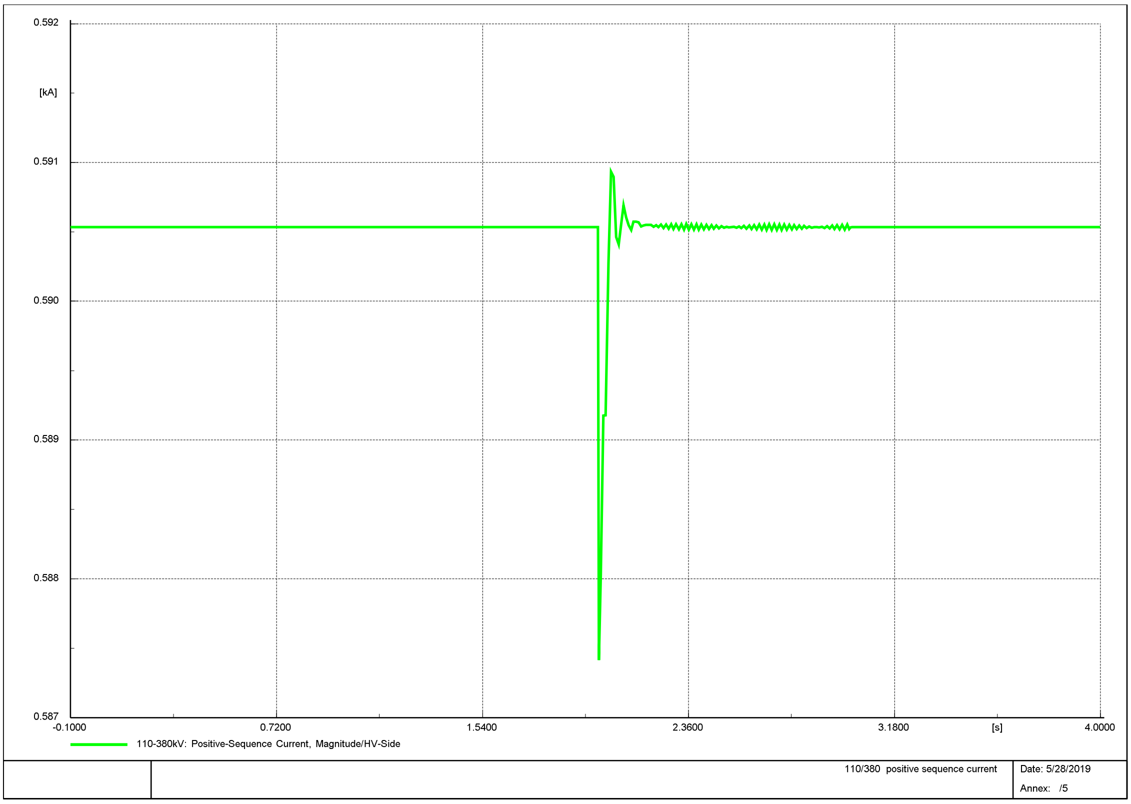

Figure 3.27 A1B1 positive sequence current, Magnitude/ HV side

the two diagrams show that the change in the current magnitude in the side of the three-winding transformer 1A1B is not large and this can be related to the correction action of the offshore inverter which can control the effects of the short circuit on the DC transmission lines.

On the other side, the onshore side at the high voltage step-up transformer 110/ 380 the change is noticeable as the current dropped down for a very short period at the starting of the fault to have a less change after that which can be explained as a result of the HVDC converters controllers action to limit the effect of the transmission line fault.

3.3.5 The System HVDC control strategy

The system can be built in many different ways and strategies where in general, the system control concept can be separated into two major parts [38], the Onshore controller and the offshore controller.

3.3.5.1 Onshore controller

The onshore controller is constructed in three controllers, the main controller, the chopper controller, and the current controller [38].

A- The main controller:

On the onshore side, the main converter which is a voltage source converter VSC as described in chapter 1,2 is functioning as to control the active and reactive current.

by controlling the active current, the converter can control the DC voltage, while by controlling the reactive current the converter can control the voltage or the reactive power (through a PI controller) [38].

As described in section in 3.3.3 of the operating of the onshore converter during the fault condition, under normal operation the converter makes the priority to the active current while limiting the reactive current, this priority changes during the fault period, the reactive current is prioritized and the active current is limited

B- The chopper controller

The objective of the chopper controller to monitor the voltage on the DC lines and give the order to ignite the DC valves of the chopper resistors in case of overvoltages. This case is mainly faced in case of the onshore fault where the transmission lines are not able to transfer the power to the gird which results in a high charge of the DC circuit and can lead to big damage on the IGBT of the converter.

C- The current controller:

The current controller objective is to take the reference current from the main controller and use it to calculate the modulation index passed to the converter[38]

3.3.5.2 The offshore controller:

The main function of the Offshore controller is to keep the offshore grid AC main parameters at fixed nominal values. mainly to keep the voltage magnitude and the frequency at constant values, thus the offshore controller is considered to build the
offshore grid voltage.

The offshore controller has also two more additional functions, these functions are:

A) In case of fault on the offshore grid network, the offshore controller has a reactive limitation action which becomes active in this case to limit the reactive current.

B) In case of a high DC voltage on the offshore grid network, the current controller has the ability to increase the frequency level on the offshore network[38].

Chapter 4

4. Conclusion

Wind energy and wind turbine technology experienced dramatic development in the last few years, Moreover, the offshore wind power installations have been developed rapidly, and the cost for offshore installations declined continuously. The power transmission system from offshore to onshore is a major part of the system which has a big effect on the efficiency of the whole system. Many research indicates the efficiency of the HVDC transmission system for an offshore wind farm greater than 100 Km from shore.

A model of offshore wind farm electrical system for simulation in Digsilent PowerFactory software is built, and short circuit events are analyzed for selected types of faults.
Faults are executed on the system as three-phase short circuits for the AC part and as a single phase to ground for the HVDC transmission line system.
The behavior of the system during the different fault condition is analyzed and the description of the short circuit at the fault location are discussed.

Three types of fault locations are implemented, onshore, offshore and on the HVDC link.
The analysis has shown that for offshore fault event in the detailed feeder on the offshore wind farm, the fault has a limited effect on the HVDC transmission line and the main consequence was on the detailed feeder its self as the protection system trip the main circuit breaker links the feeder to the AC busbar in the offshore station and isolated the faulted feeder (10 Turbines) only.
The main HVDC transmission line continues to supply the grid with power by the rest of heathy wind turbines from the other feeders.

This can be explained by the small voltage drop on the HVDC terminals (relating to the fault even), this drop didn't go below 0.8 pu, thus the protection system of the HVDC is not activated. This small drop in voltage is related to the impedance of the three-winding transformers on the offshore substation which limits the short circuit current value.
In the case of Onshore fault event, in this case, the produced power by the wind farm on the offshore side are not been able to be transferred through the onshore converter to the onshore side and the grid, this can result in high voltage level on the HVDC terminal and can lead to damage the IGBT in the converting system. To avoid that critical situation, the chopper controller which is part of the onshore control gives the order to ignite the DC valves of the chopper resistors to discharge the overvoltage of the DC circuit.

The third case, the fault on the HVDC transmission line is also discussed and the plotted diagrams for the current in the offshore and onshore part are executed.
the diagrams illustrates that the effects of the fault event on the HVDC transmission line is limited on the offshore and onshore elements, this can be explained by the role of the two voltage source converters on offshore and onshore, these converters limits the level of the negative effects of the HVDC fault on the elements existing on the both side of the line.

finally, the study can be extended for more detailed discussions and different farm types with different methodologies, such as AC transmission lines or Series -DC collection system.

Bibliography

[1] Ribrant, J., & Bertling, L. (2007, June). Survey of failures in wind power systems with a focus on Swedish wind power plants during 1997-2005. In *2007 IEEE power engineering society general meeting* (pp. 1-8). IEEE.

[2] Al-Majed, S. I., & Fujigaki, T. (2010, September). Wind power generation: An overview. In *2010 Modern Electric Power Systems* (pp. 1-6). IEEE.

[3] Europe, W. (2018). Offshore Wind in Europe: Key Trends and Statistics 2017. Via Internet (10.10. 2018)< https://windeurope. org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2017. pdf.

[4] https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf

[5] Molina, M. G., & Mercado, P. E. (2011). Modeling and control design of pitch-controlled variable speed wind turbines. In *Wind turbines*. IntechOpen.

[6] Duong, M. Q., Grimaccia, F., Leva, S., Mussetta, M., Sava, G., & Costinas, S. (2014). Performance analysis of grid-connected wind turbines.

[7] Chen, Z., Guerrero, J. M., & Blaabjerg, F. (2009). A review of the state of the art of power electronics for wind turbines. *IEEE Transactions on power electronics*, *24*(8), 1859-1875.

[8] Yang, J. (2011). Fault analysis and protection for wind power generation systems (Doctoral dissertation, University of Glasgow).

[9] Yang, X., Patterson, D., & Hudgins, J. (2012, July). Permanent magnet generator design and control for large wind turbines. In 2012 IEEE Power Electronics and Machines in Wind Applications (pp. 1-5).

[10] Zhang, Z., Chen, A., Matveev, A., Nilssen, R., & Nysveen, A. (2013). High-power generators for offshore wind turbines. Energy Procedia, 35, 52-61.

[11] da Silva, F. F., & Castro, R. (2009). Power flow analysis of HVAC and HVDC transmission systems for offshore wind parks. International Journal of Emerging Electric Power Systems, 10(3).

[12] Deng, F., & Chen, Z. (2011, July). An offshore wind farm with DC grid connection and its performance under power system transients. In 2011 IEEE Power and Energy Society General Meeting (pp.

[13] Reed, G. F., Al Hassan, H. A., Korytowski, M. J., Lewis, P. T., & Grainger, B. M. (2013, May). Comparison of HVAC and HVDC solutions for offshore wind farms with a procedure for system economy

[14] Xu, L., & Andersen, B. R. (2006). Grid connection of large offshore wind farms using HVDC. Wind Energy, 9(4), 371-382.

[15] Kling, W. L., Hendriks, R. L., & Den Boon, J. H. (2008, July). Advanced transmission solutions for offshore wind farms. In *2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century* (pp. 1-6). IEEE.

[16] Nazari, M. (2017). *Control and Planning of Multi-Terminal HVDC Transmission Systems* (Doctoral dissertation, KTH Royal Institute of Technology).

[17] Hansen, A. D., Cutululis, N. A., Markou, H., Sørensen, P. E., & Iov, F. (2010). Grid fault and design-basis for wind turbines-Final report.

[18] Hansen, P., Østergaard, J., & Christiansen, J. S. (2007). System grounding of wind farm medium voltage cable grids. In *4th Nordic Wind Power Conference*.

[19] Gharehpetian, G. B., & Agah, S. M. M. (Eds.). (2017). *Distributed Generation Systems: Design, Operation, and Grid Integration*. Butterworth-Heinemann.

[20] Zhao, H., & Cheng, L. (2017). Open-circuit faults diagnosis in back-to-back converters of DF wind turbine. *IET Renewable Power Generation*, *11*(4), 417-424.

[21] Hunt, R., Cardenas, J., Muthukrishnan, V., & McGinn, D. (2010, March). Wind farm protection using an IEC 61850 process bus architecture. In *2010 DistribuTech Conference & Exposition*.

[22] Shah, S., Guo, H., & Sun, J. (2014, November). Fault analysis and protection of series-dc collection system for offshore wind power plants. In *Proc. 13th Wind Integr. Workshop* (p. 6).

[23] Suwan, M. (2017). *Modeling and Control of VSC-HVDC Connected Offshore Wind Farms* (Doctoral dissertation, Duisburg, Essen, Universität Duisburg-Essen).

[24] Peng, L., Francois, B., & Li, Y. (2009, February). Improved crowbar control strategy of DFIG based wind turbines for grid fault ride-through. In *2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition* (pp. 1932-1938). IEEE.

[25] Erlich, I., Kretschmann, J., Mueller-Engelhardt, S., Koch, F., & Fortmann, J. (2008, July). Modeling of wind turbines based on doubly-fed induction generators for power system stability studies. In *2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century* (pp. 1-8). IEEE.

[26] Kusiak, A. (2010). *Wind power systems*. L. Wang, & C. Singh (Eds.). Springer-Verlag Berlin Heidelberg.

[27] Peng, L., Francois, B., & Li, Y. (2009, February). Improved crowbar control strategy of DFIG based wind turbines for grid fault ride-through. In *2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition* (pp. 1932-1938). IEEE.

[28] Anaya-Lara, O., Campos-Gaona, D., Moreno-Goytia, E., & Adam, G. (2014). *Offshore wind energy generation: control, protection, and integration to electrical systems*. John Wiley & Sons.

[29] Olguin, R. E. T., Garces, A., & Bergna, G. (2014). HVDC transmission for offshore wind farms. In *Large Scale Renewable Power Generation* (pp. 289-310). Springer, Singapore.

[30] Xu, L., Yao, L., & Sasse, C. (2007). Grid integration of large DFIG-based wind farms using VSC transmission. *IEEE Transactions on Power Systems*, *22*(3), 976-984.

[31] Flourentzou, N., Agelidis, V. G., & Demetriades, G. D. (2009). VSC-based HVDC power transmission systems: An overview. *IEEE Transactions on power electronics*, *24*(3), 592-602.

[32] Hamon, C., Elkington, K., & Ghandhari, M. (2010, October). Doubly-fed induction generator modeling and control in DigSilent PowerFactory. In *2010 International Conference on Power System Technology* (pp. 1-7). IEEE.

[33] DIgSILENT PowerFactory 2018, Template documentation, IEC 61400-27-1(WTG Models)

[34] DIgSILENT PowerFactory 2018, Technical Reference Doubly-Fed Induction Machine (ElmAsmsc, TypAsmo)

[35] DIgSILENT PowerFactory 2018, Technical Reference Three winding transformer (Elm Tr3, TypTr3)

[36] DigSilent Power Factory 2018 user manual, DIgSILENT GmbH Heinrich-Hertz-Straße 972810 Gomaringen / Germany.

[37] Liu, Y. W., Chen, Z. H., & Shen, J. (2012). Application of PLL in the Generator-side Converters for Doubly-Fed Wind Power Generation Systems. *Energy Procedia*, *16*, 1822-1830.

[38] HVDC connected Offshore wind farm application examples, DigSilent Powerfactory 2018, DIgSILENT GmbH Heinrich-Hertz-Straße 972810 Gomaringen / Germany