INNOVATIVE TOOLS FOR OFFSHORE WIND AND DC GRIDS

Deliverable 2.1 – Work Package 2: Progress report on review and evaluation of OWPP control systems, collection configurations & transmission technologies, offshore electrical resonance instability phenomenon.

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1. Collection configurations and transmission technologies

The section of this report describes the collection configurations and transmission technologies for offshore wind power plants (OWPPs).The objective is to analyse the most promising solution proposed by researchers and manufacturers during the last few years.

1.1 Collection systems

1.1.1 MVAC collection systems

1.1.1.1 Radial

In the radial collection system, a number of wind turbines are connected to a single feeder in string configuration as shown in Figure 1.1. The maximum number of wind turbines that can be connected to one feeder is determined by the cable ampacity and capacity of the generators [1]. Advantages of this system are easy control and small total cable length why it is also considered as a cheapest option. The main drawback is its low reliability, as cable or switchgear faults at the hub end of the string will cause full power generation loss from all downstream turbines [2].

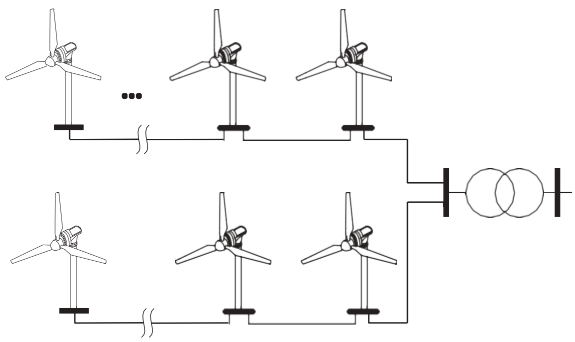

Figure 1.1 Radial collection configuration [1]

1.1.1.2 Ring

With additional cabling, the ring collection system (shown in Figure 1.2) can overcome the reliability issues, but also increases the cost due to the use of longer cables and higher cable ratings [3]. Depending on how the ring is formed there are: single-sided, double-sided and multi-ring. In all cases, redundant cables are added in order to increase the possibilities of the transmission of power [1]. A single-sided ring design requires an additional cable run from the last wind turbine to the hub for each string, while the double-sided ring layout interconnects the last wind turbine in one string to the last wind turbine in the next string. During the fault condition, the full output power of the wind turbines in one of the strings has to be redirected through the other string, so the cable at the hub end needs to be sized for the power output of double the number of wind turbines which represents the main disadvantage of this configuration [3] [4].

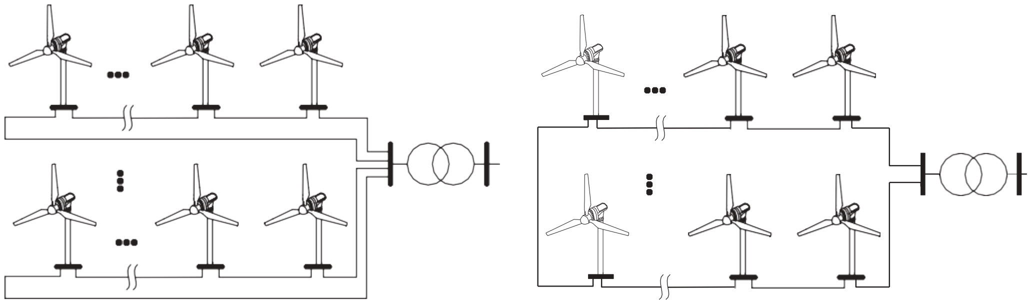

Figure 1. 2 Ring collection configuration [1]

1.1.1.3 Star

The star collection system is a way to reduce the cable ratings of the cables which connect the wind turbines and the collector point located in the middle of the grouping of all wind turbines, as seen in Figure 1.3. This system provides a high level of security for the wind farm, since a cable outage causes the loss of only one machine. Using longer cable lengths and lower voltage ratings for the connection of wind turbines in this configuration, increase the cable losses and their costs than in other WPP designs [1].

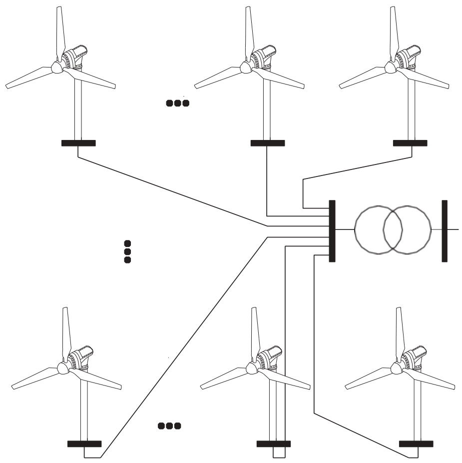

Figure 1.3 Star collection configuration [1]

1.1.2 MVDC collection systems

1.1.2.1 Shunt Topology

The main characteristics of this topology is that the output voltage of each wind turbine is kept constant, while the current flowing through the inter-array cables depends on the number of tur- bines connected on it [1]. There are many possible collection systems based on shunt topology depending on number of DC/DC transformation steps and number of collector/offshore platforms:

- Configuration 1: This shunt topology (Figure 1.4) consists in connecting all the DC cables directly to the offshore HVDC converter platform. One step-up stage is used where the output voltage of each wind turbine is stepped-up by a DC/DC power converter [1].
- Configuration 2: In this scheme (Figure 1.5) an offshore collector platform is added to gather all the inter-array cables. Thereby, the wind turbines are connected to the collector platform by means of the inter-array cables, while the export cable connects the collector platform with the HVDC offshore platform. The step-up stage is same as in the previous case [1].

• Configuration 3: Due to big export cable losses (too low system voltage), this DC OWPP proposal is based on installing a DC/DC power converter in the intermediate offshore platform (Figure 1.6). The result is having two step-up stages (both at the wind turbine and the collector platform level) [1].

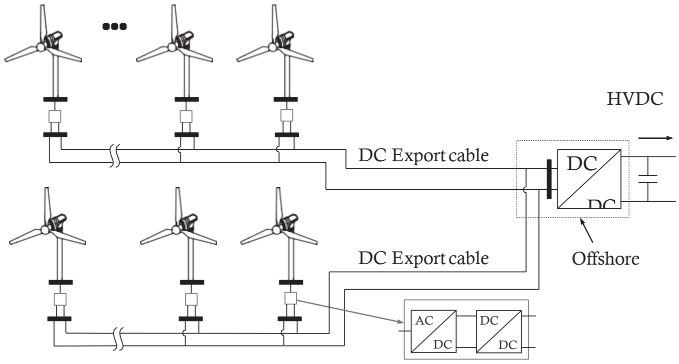

Figure 1.4 Proposal of the DC OWPP configuration 1 [1]

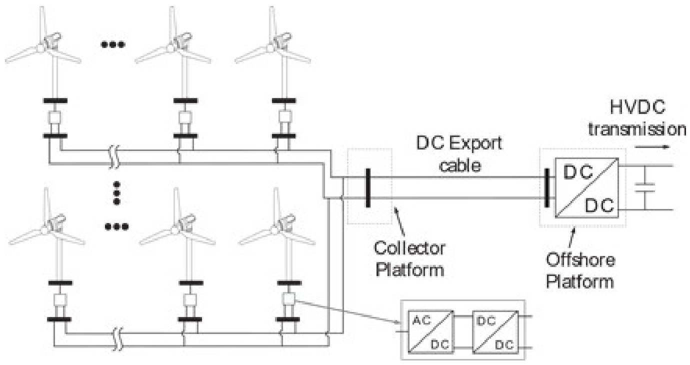

Figure 1.5 Proposal of the DC OWPP configuration 2 [1]

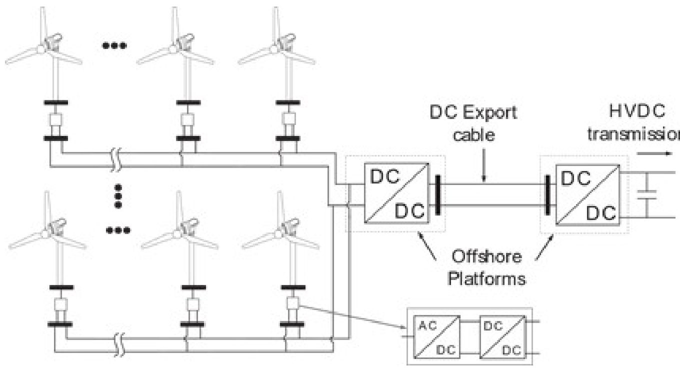

Figure 1.6 Proposal of the DC OWPP configuration 3 [1]

• Configuration 4: This scheme differs from the previous one in installing one DC/DC power converter per feeder at the intermediate collector platform in attempt to increase the reliability of the system (Figure 1.7). Its disadvantages are more power electronic components and the intermediate offshore platform should be bigger, leading to higher losses and increased cost [1].

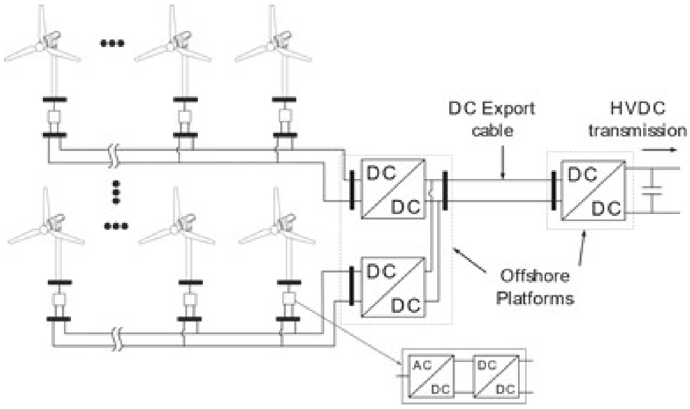

Figure 1.7 Proposal of the DC OWPP configuration 4 [1]

1.1.2.2 Series Topology

The turbines are connected in series, as in the Figure 1.8. As a result, the output voltage is increased to transmission levels and the current of each wind turbine is kept constant. The aim is to eliminate offshore converter platform. The main drawbacks are the approach in regulating the voltage instead of the current and the oversizing of some electrical components of the wind farm to the maximum power of the whole wind farm [1].

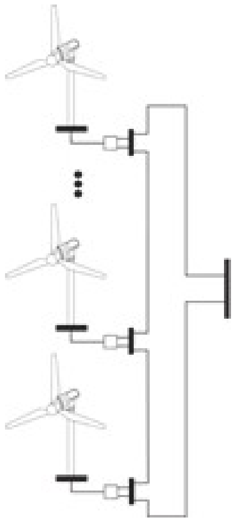

Figure 1.8 Series collection configuration [1]

1.1.2.3 Hybrid Topology

The hybrid topology is defined as a combination of both previous topologies. It is designed as a short number of wind turbines electrically connected in "series" but the feeders are connected in "shunt" between them (Figure 1.9). The problems are same as in the previous case, but the oversizing is less notable, as only few turbines are connected in series. The problems are same as in the previous case, but the oversizing is less notable, as only few turbines are connected in series [1].

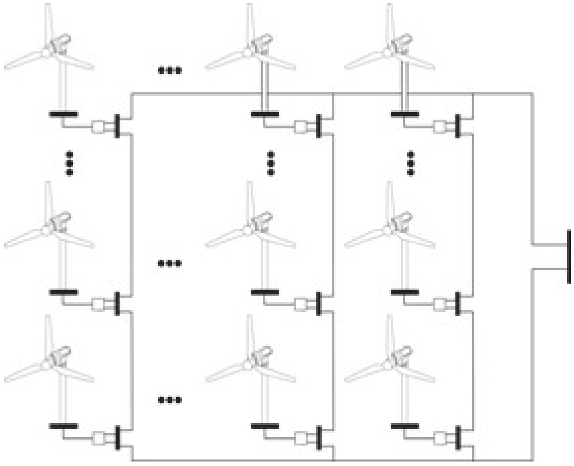

Figure 1.9 Hybrid collection configuration [1]

1.2 Transmission technologies

1.2.1 HVAC transmission

HVAC transmission systems for OWPPs usually are composed of two substations which are connected with cross linked polyethylene (XLPE) submarine cables. The substations include power transformers, gas or air insulated switchgear and reactive power compensation equipment [5]. Through reactive power compensation the voltage and frequency are controlled. Fixed compensation is used at the offshore and static VAR compensators (SVCs) at the onshore substation with the purpose of maintaining the voltage (Figure 1.10). Recently static synchronous compensator (STAT- COMs) have replaced SVCs, and in some cases shunt reactors are required for an appropriate P-Q control at the turbine level.

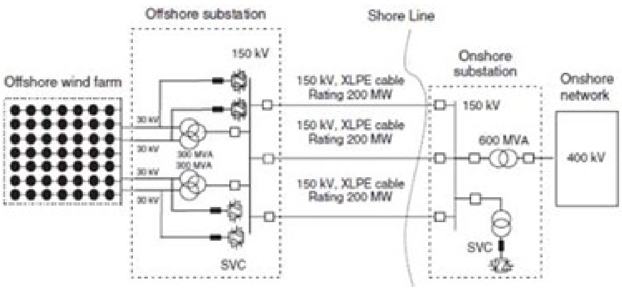

Figure 1.10 Basic configuration of HVAC solution [6]

Regarding the cables, XLPE cables are the standard for HVAC transmission systems as well as for MVAC collector systems. They can be either single-core or three-core, but today three-core cables have the advantage due to reduced power losses and less installation costs [2].

A step-up offshore transformer is necessary because the voltage level in the offshore wind farm is usually in the range of 30kV-36kV and the transmission level is usually in the range of 110kV to 400kV. An onshore transformer is also needed depending on the grid voltage which is usually different than the offshore transmission rated voltage [6].

The main challenges to optimize AC offshore substations are the power export availability and protection of equipment in marine environment (minimizing corrosion damage). A higher degree of redundancy increases the availability, such as installing two

60-70% rated transformers instead of one or enabling ring collection system designs by additional space for bigger switch gear at the substations [2]. The reactive power generated in the cables increases with the cable length and therefore limits the active power that will be delivered to the grid and the cable length of the offshore transmission link. That leads to high costs and difficulties in installing reactive power compensation along the cables which are the main reasons that today there are other proposed systems discussed further in the report.

1.2.2 HVDC transmission

The converter technologies used for HVDC transmission systems for offshore wind have been line commutated converters (LCCs) and voltage source converters (VSCs). But there are several reasons not to consider LCC as a proper choice for OWPPs. When connected to weak AC grids, the number of commutation failures is big. The reason is that the system is based on thyristors that require strong network voltage for commutation so STATCOMs or capacitor banks are required in order to provide control over the reactive power and to help ride through the AC system fault (Figure 1.11). One more limitation it doesn't have a black start capability. That is why a diesel generator is required at the offshore station to generate the voltage required to start the commutation process. The HVDC LCC system needs AC and DC filters because of a high level of harmonic content. Due to a large number of elements, LCC converter stations require a lot of space, which increases the size and the costs of the offshore substation platforms.

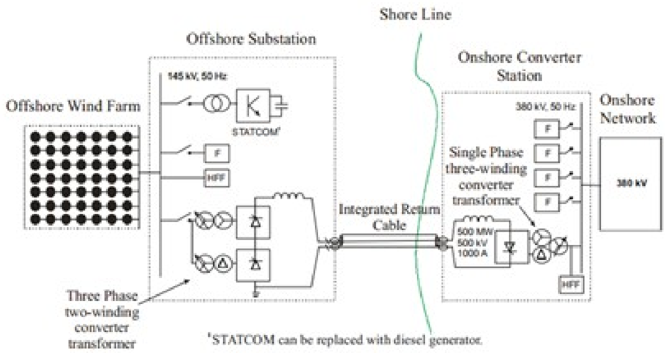

Figure 1.11 Basic configuration of HVDC LCC solution [6]

On the other hand, HVDC VSC is constructed from two system elements, including two con- verter stations (one offshore and one on shore) and a pair of polymeric extruded cables. One of the converters operates as a rectifier and the other as an inverter at variable frequency, so the result is both absorption or delivery of reactive power to the AC grid. Also, there is no limitation on cable length compared to the HVAC system because there are no reactive power losses along the line. In this system active and reactive power supply can be controlled independently providing voltage and frequency stability as opposed to the HVDC LCC system [6]. HVDC VSC uses IGBT semi- conductor technology with a switching frequency usually between 1.3 and 2.0kHz which reduces the number of harmonics in the system, so the amount of filtering is less needed as compared to VSC LCC systems. HVDC VSC is not so space demanding as to HVDC LCC systems, therefore it is a more suitable solution for offshore applications. Figure 1.12 shows a basic HVDC VSC system configuration for offshore wind farms.

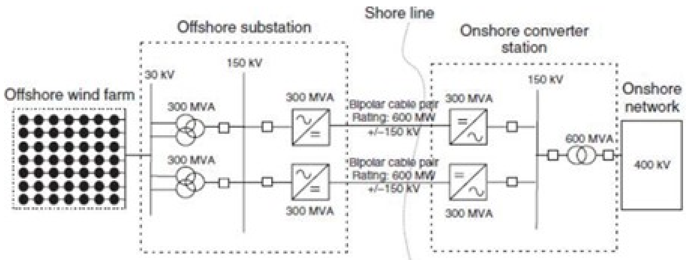

Figure 1.12 Basic configuration of HVDC VSC solution [6]

In the past mainly VSC schemes that were used were based in two level converters and three level neutral point clamped converters. The main disadvantage is that the power losses are 2% per converter station. Having high switching frequency in order to reduce harmonics also results in having high switching losses in the valves of the converter. That is why today VSC-HVDC converters based on multi-modular converter (MMC) technology are applied. The increased number of voltage steps leads to very low levels of harmonic distortion and the loss rate is around 1% per converter station. [2]

1.2.3 Other transmission technologies

1.2.3.1 LFAC transmission systems

LFAC systems work at a smaller frequency (usually one-third of the grid frequency value). This value is created with a presence of a frequency converter using Back-to-Back (B2B) technology illustrated in Figure 1.13. The use of LFAC technology increases the amount of transmitted power and transmission distance for a given submarine cable compared to 50-Hz or 60-Hz HVAC, as at a low frequency the charging current and reactive power are significantly lower. The diminished requirements for the selection of the cables and the possibility of using the normal ac breakers for protection decrease the overall costs [7].

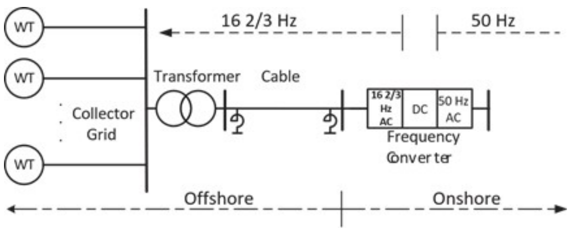

Figure 1.13 Basic configuration of LFAC solution [8]

The maintenance costs are reduced as well, as the frequency converter that synchronizes the frequencies between the LFAC system and the main grid AC system can be installed onshore [9]. Also the low frequency can influence the collection system as the mechanical design of the wind turbine can be simplified (Permanent Magnet Synchronous Generator (PMSG) would have less pole pairs and Double Fed Induction Generators (DFIG) would have lower ratio gearbox).The main disadvantage is the size of transformers, as low frequency requires larger transformers, which also leads to bigger offshore substations [5].

1.2.3.2 Diode based HVDC transmission

This configuration (Figure 1.14) is based on the diode rectifier which brings several benefits like cost reduction, higher efficiency and transmission capacity. On the other hand, the diode rectifier produces large current harmonics, so a big filter bank is necessary.

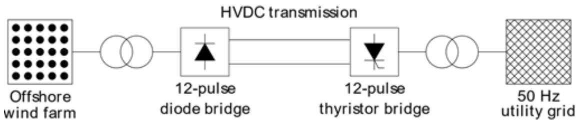

Figure 1.14 Point-to-point HVDC link based on diode-rectifier [5]

As the offshore diode bridge is uncontrollable, there is an improved scheme by adding a 12- pulse diode rectifier with a VSC at the offshore side shown in Figure 1.15. The VSC allows to control the AC collection grid at constant frequency. It can be also used as an active filter to absorb the harmonics [5]. Siemens investigated this topology and the results shown that the possible achievements will be 80% less volume, 65% less weight, 20% less transmission losses. This will reduce the cost around 30% compared to conventional HVDC-VSC configuration [10].

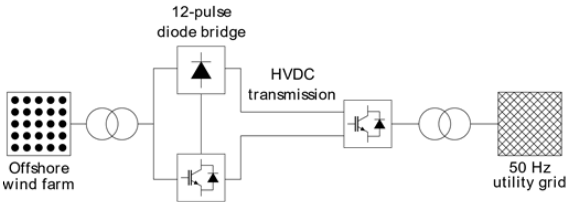

Figure 1.15 Point-to-point HVDC link based on diode-rectifier [5]

1.2.3.3 Multi-terminal HVDC transmission

Multi-terminal HVDC-VSC systems are composed of a number of different converters which are connected to a common HVDC circuit. The potential of offshore wind farms has led to creating such systems in the energy planning of a number of countries. The design is determined by technical-economic factors and criteria established by the grid utility to which the system will be connected. The costs of system depend on the circuit lengths, ratings of the converters, the number of HVDC circuit breakers and isolators and the need for offshore platforms and fast communications [11]. The current unavailability of appropriate HVDC breakers and DC protection systems limits the feasibility of multi-terminal VSC-HVDC transmission systems, as without them, the whole system voltage would have to be brought to zero in order to clear a fault [2]. Among high voltage equipment manufacturers, appropriate DC circuit breakers are expected to be commercially available. However, it has to be taken into account that the costs of these DC circuit breakers will be considerably higher than comparable components in AC grids [12].

In [1] and [11], the authors suggest the following schemes:

- Point-to-point topology (PPT): It is shown in Figure 1.16. It is based on several point to point links. In a case of a converter or HVDC circuit failure, the faulted line is disconnected by opening the AC circuit breakers of the grid side converter and let the turbines trip off on over-speed. If there is a fault on a line, the power from the connected wind farm will be lost. In conclusion non-flexibility is the main drawback of this configuration.

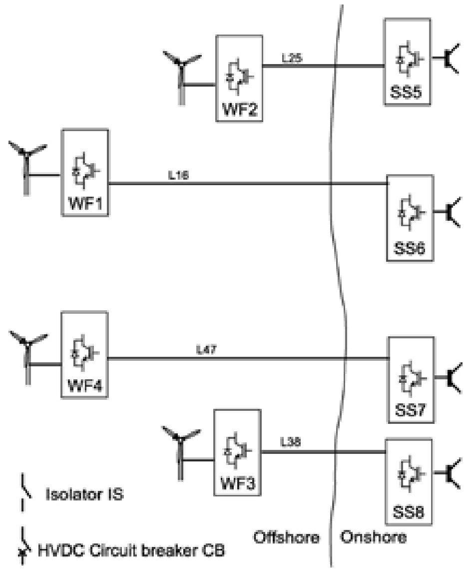

Figure 1.16 Point-to-point topology [11]

• General ring topology: In this configuration there are lines formed in a ring connecting all the substations (Figure 1.17). The system can be normally operated in a closed loop. The benefit of this system is that in a case of fault, there will be no power losses, as the other lines are rated to the whole power of the system.

• Star topology: Each transmission line attached to a wind farm or substation is connected to a central star node (ST), and star with a central switching ring topology, where the central star node of the previous topology is implemented with a central switching ring (SGRT) as shown in Figure 1.18 and Figure 1.19 respectively. The difference is in ST a fault at the central node can cause the entire system to shut down while in SGRT the fault can be isolated while having the lines in the central ring rated at full power of the whole system. The main drawbacks of both is that a full wind farm is lost for a permanent fault in a line from the central node to a wind farm and needing an offshore platform for all circuit breakers.

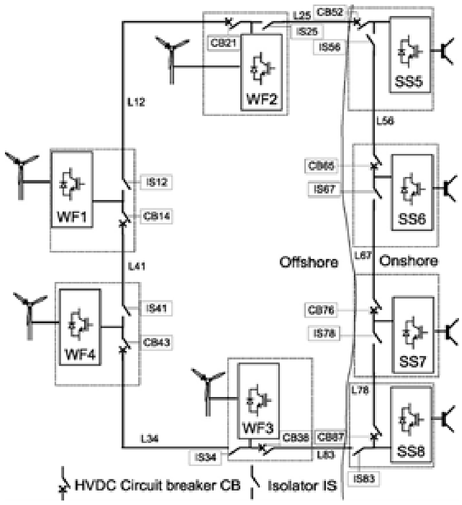

Figure 1.17 General ring topology [11]

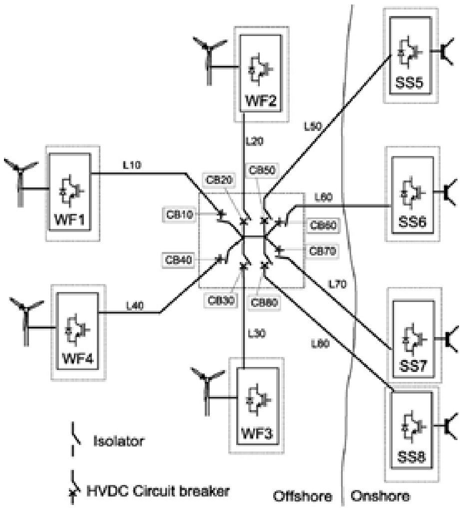

Figure 1.18 Star ring topology [11]

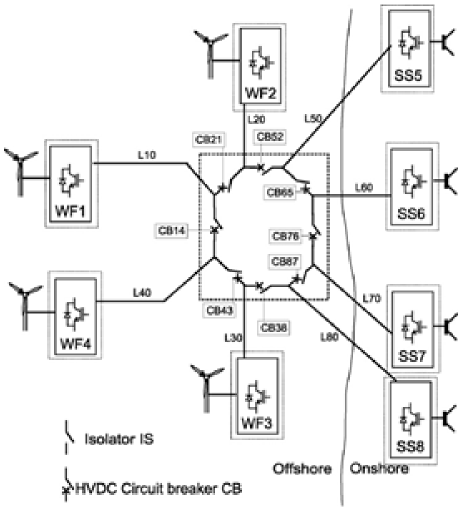

Figure 1.19 Star with a general ring topology [11]

• Wind farms ring topology: This topology is formatted as a ring of wind farms which has the same number of HVDC circuit breakers as the number of wind farms and circuits connected to the substations, which reduced the total number of circuit breakers compared to other topologies (Figure 1.20). It resembles to the PPT but with increased flexibility of controlling the power flow between wind farms and land based substations. In case of a line fault, the faulted line can be isolated as in PPT but with no power loss of the wind farm as it can be reconnected to another substation. During a circuit fault, the two HVDC circuit breakers are opened and in that way dis- connecting the wind farm and the substation. This configuration is adjustable to all fault situations but it requires fast communications to coordinate the HVDC protection.

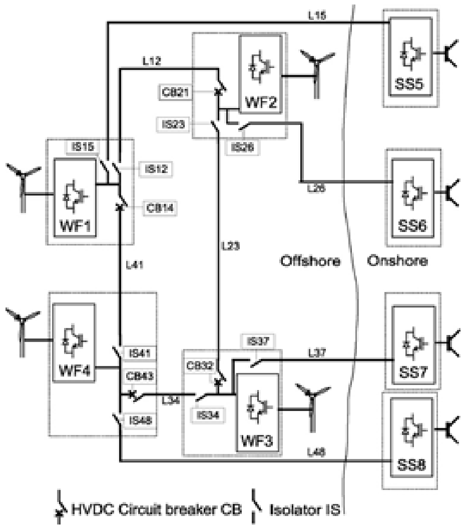

Figure 1.20 Wind farms ring topology [11]

• Substations ring topology: As it is illustrated in Figure 1.21 substation ring topology is similar to WFRT. When there is a fault in a HVDC line, the HVDC-VSC converter of the wind farm is isolated unlike the main grid HVDC-VSC in WFRT configuration. ORIOL It allows more flexibility on the grid side at the cost of losing the production of an OWPP during long term failures and maintenance operations in its link. The topology will be more applicable than WFRT, since faults in the HVDC circuits will allow uninterrupted extraction of all the power from the wind farms.

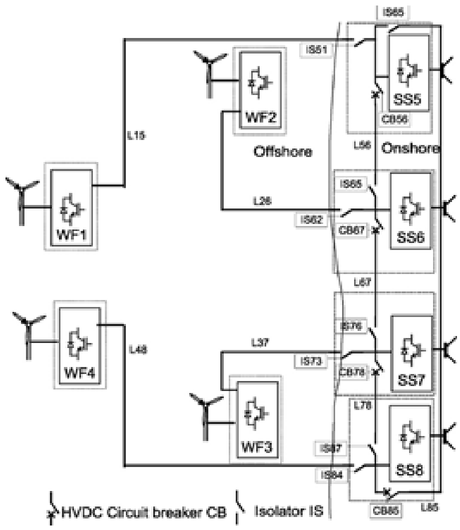

Figure 1.21 Substations ring topology [11]

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2. Review and Evaluation of DC Collection systems for harnessing Offshore Wind Power

2.1 Introduction

As no industrial project as of today envisage an all-dc wind park, it is more interesting to turn to the research world where all-dc park concepts with series connection of wind turbines have been considered for a while. As discussed in Chapter 1 there are several system topologies which can be utilised in DC collection systems. An approach taken by some authors is to consider clusters of turbines [1]. The main advantage of DC series and DC Series-Parallel (SP) topologies is that a high transmission voltage is obtained when summing up the individual turbine voltages and no step-up transformer is needed as shown in Figure 2.1. Thus, it is possible to reduce the size and weight of individual wind energy conversion unit and expensive offshore platform with transformer, AC-DC, or DC-DC converter is not required as a dc voltage high enough for transmission is build up by the series connection of turbines [2]. The classical AC collection system requires a platform-supported transformer and AC–DC converter which will present a significant share of the total loss. This is due to DC series collection system can present an advantage in terms of efficiency if the loss of the Wind Energy Conversion System (WECS) inside the turbines are minimised. From the transmission

A technical challenge of the series connection is the insulation to ground of the last turbines in the chain as the potential will be the added output voltage of each turbine. Mainly the concepts can be separated into conversion system featuring an isolation transformer and those without [3–5].

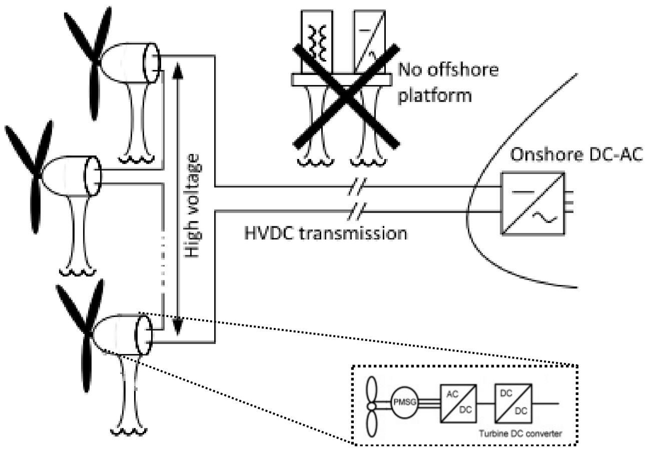

Figure 2.1 A platform less offshore wind power DC collection system [2]

An overview of OWPP DC collection system with regard to various aspects is shown in Figure 2.2. It is important to note that DC-DC converter plays an important role in DC collection system which acts as the interface between grid side converter and wind turbine converter in offshore wind platform-less collection systems. Several topologies of isolated DC–DC converters including the full bridge DC–DC converter, single active bridge converter, and resonant converters were studied, and their energy efficiencies were compared in [6]. Research on finding a suitable DC–DC converter topology for DC collection systems is still ongoing and several novel topologies of high power DC–DC converters have been proposed in [7,8]. A novel resonant zero-voltage-zero-current switching (ZVZCS) DC–DC converter with two uneven transformers has been proposed [7] for an MVDC collection system of OWPP which can minimise switching losses. A modular DC-DC converter with input-series-input-parallel output-series connection to realise a DC collection power network for large-scale offshore wind farms was presented in [8]. This proposed topology uses interconnection of multiple modular cells with low rated voltage and power to enable operation with high voltage at the input and output.

However, the main objective of this section is to address major technical challenges associated with OWPP DC collection systems. Hence a detailed review on DC-DC converts applicabl

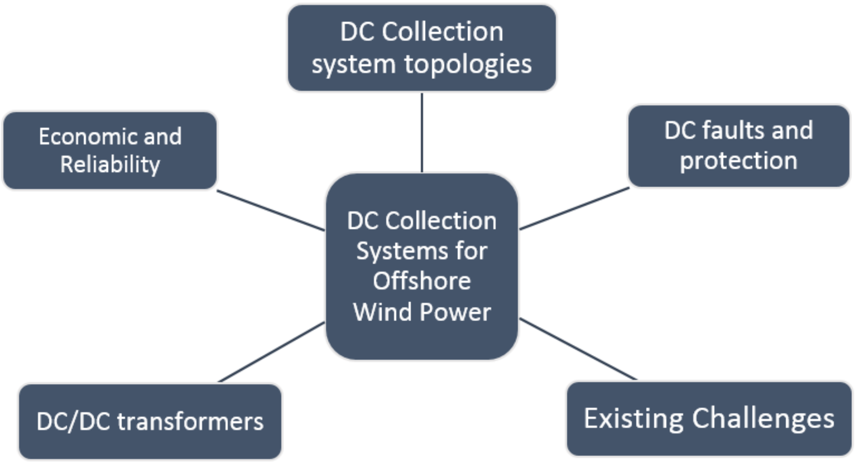

Figure 2.2 Various technical aspects on Offshore wind power DC collection systems

The rest of the sections are arranged as follows. In Sec. 2.2 existing technical challenges related to DC collection systems are presented. Then several economic and reliability assessments conducted in the literature are discusses in Sec. 2.3. Next, DC fault handling and protection requirements are also discussed in brief in Sec. 2.4. Finally, future research directives in DC collection systems to integrate offshore wind power is presented.

2.2 Technical challenges in DC collection systems

Existing technical challenges associated with different DC collection systems have created new research directions aiming to understand and provide feasible solutions. In the existing literature the following issues have been identified as technical barriers in developing DC collection systems for offshore wind power plants;

1. Over voltage and Under voltage issue associated with DC series and DC Series-Parallel (SP) topologies
2. Minimising overall system losses
3. Stability issues related to DC collection system

Apart from these major technical barriers, power quality issues such as current and voltage harmonics, voltage flicker, sag, swell are integral features of power electronics rich systems.

2.2.1 Over voltage and under voltage issue

In conventional wind farms, maximum power operation is guaranteed by the control of individual power converters for each wind turbine, whereas in the case of a DC series–parallel connected offshore wind farm, the individual wind turbines cannot be operated at maximum power all the time. Wind speed differences cause unequal voltages at the DC output of the turbines because of the series connection. The string voltage (HVDC transmission voltage) must be shared by the individual wind turbine DC–DC converters proportional to the power output of the wind turbines [9]. This will result in some of the series connected wind turbines with high output power experiencing over-voltage and wind turbines with low output power experiencing under-voltage at their DC outputs. As a solution for this issues [9] propose an energy curtailment strategy for safe operation of entire DC collection system without cascade tripping. Further analysis shows that the monetary equivalent of the lifetime curtailment losses is estimated to be 55% of the platform costs for a worst-case scenario considered. This suggest the feasibility of SP collection topology

In [10] a novel topology of voltage balance circuit for DC parallel wind farm configuration is proposed to eliminate over voltage issue. In the proposed topology, adjacent wind turbines are connected by a voltage balance circuit in parallel, and these wind turbines can both achieve the maximum power point tracking (MPPT) and balance the terminal voltages when the wind speeds of wind turbines are unequal. This is achieved via current compensation of voltage balance circuit which can ensure the normal operation of wind farm even if some wind turbines are outage.

Reducing the string voltage could be another solution to reduce the probability of string failure condition. The proposed matrix interconnected (MI) topology in [11] benefits from the extra connection paths between the branches that allow the reconfiguration of the collector system following failure conditions. Proper topology change mitigates the overvoltage of units upon failure occurrences and enhances the efficiency of the wind farm.

A global control strategy is proposed in [12] for MMC-HVDC based SP topology that prevents wind turbines from operating above their overvoltage capabilities. With an active participation of the onshore converter, the proposed strategy allows maximum power point tracking (MPPT) of the wind turbines.

2.2.2 Overall system loss reduction

Losses are unavoidable in any practical system and it plays a vital role in the entire performance of a wind farm collection system configuration. Each and every component in a particular configuration contributes to the overall system loss and various methodologies have been adapted for minimising losses. Since DC collection systems are rich with power electronic devices major portion of the system loss comes from switching losses. As discussed in the introduction deploying novel DC-DC converter topologies shall minimise switching losses [13, 14].

There are number of configuration that can be developed to for a DC collection system. As shown in configurations of Figure 2.3, a comparative analysis has been carried out in [15] over basic DC collection system configurations in [13], which suggests in terms of losses the use of a two-level system together with a high-power converter system in Fig 03 (b) is preferable. Other than these configurations by eliminating centralised offshore collector platform, DC-SP topology have minimum converter losses as discussed in [15] compared to AC collection systems.

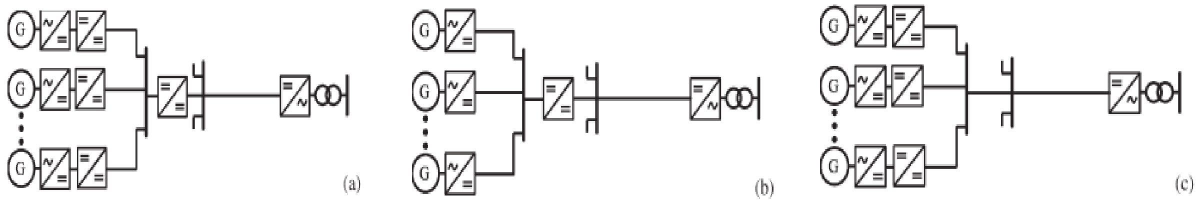

Figure 2.3 Different configurations for the dc grid. (a) Two step-ups. (b) One cluster step-up. (c) Turbine step-up [13]

Loss models are necessary in order to realise optimum wind farm configuration. In [16], a detailed cable model, transformer (core and cooling losses) and converter loss models have been developed to calculate power losses in of both AC and DC OWPP collection systems and transmission systems. These are the main components of losses under steady-state operation. The case-study results show that the proposed models are able to capture the main sources of power losses, as well as, the main environmental factors, such as type of soil surrounding the cables and ambient temperature in an offshore wind farm.

2.2.3 Stability issues related to DC collection system

In a DC collection system, instability of individual terminal controls and resonance in the dc link voltage and/or current may occur when connected to a weak ac grid. Further, this instability may cause with improper control design. However, existing options for controlling DC-SP topology are limited. For the series-dc system described in [17-19] that uses current source converters (CSC) as sending terminals, the onshore inverter is assumed to set the dc link current, while each sending terminal regulates its dc output voltage. This method cannot be used when there is more than one string of series-connected terminals, as the distribution of the total dc link current among parallel strings will be highly dependent of the string voltages and cannot be individually controlled by the receiving terminal.

To address these challenges, [20] presented a new framework for local control design and the stability analysis of dc power systems. The proposed approach overcomes the limitations of existing control methods, especially when applied to the DC-SP topology and other new architectures, and allows local controls to be designed for individual terminals independent of other terminals.

2.3 Economic Analysis

To measure the economic viability of offshore wind power DC collection systems over AC collection systems, several comparative studies of different collection system configurations have been performed in the literature.

Not only losses are contribute to economic assessments but also operation and maintenance costs (O&M), reliability (component failure rates, maintaining system redundancy) are also important factors. The maintenance cost can be classified into preventive and corrective maintenance cost. The preventive maintenance cost is associated with the energy losses due to planned maintenance, which causes partial or complete outages in the wind farms to prevent any possible damage of its components. The cost associated with the preventive maintenance losses is small because such maintenances are normally carried out during the period of low wind days when the energy yield is small. The cost associated with the corrective maintenance losses is due to the unplanned nature of the maintenance, which occurs following the failure of the wind farm components. If these types of failure occur during adverse weather conditions, then unlike the preventive maintenance costs, the corrective maintenance costs can be expensive. The corrective maintenance cost can be estimated by performing a reliability analysis of the collection configurations considered. This would require the failure rates and repair times of the collection system components to estimate the Expected Energy Not Supplied (EENS) indices.

This corrective maintenance cost will be different for each of the collection systems considered because it depends on the failure rates and the repair time of the collection system components. The reliability data, such as the failure rates and repair times, are readily available for the AC collection systems from the experiences of the commissioned offshore wind farms [21], whereas such information is not available for the DC collection configurations, especially the failure rates and repair times of DC–DC converters with the medium frequency transformers and DC circuit breakers, because of lack of operational experiences. However, from the point of view of reliability, DC collection systems may not be a favourable choice as they depend more on power electronic converters and the failure rates of converters are higher than those of transformers

The DC series connection of wind turbines was compared with AC radial transmission in [22]. The cost and losses of the offshore wind farms based on centralized power electronic converters [23] were compared for AC and DC configurations. In the AC and DC collection comparative study [24], DC series and DC series-parallel collection systems were identified as cost effective. In [15] an approximate cost assessment study was carried out considering the costs of investment and losses for the collection system components. This includes the collection cables, power electronic converters, switch gear and offshore platforms. The cost for individual components was calculated based on the cost models described in [15] for both the AC and DC collection system components and results show that the losses in the DC collection systems are higher than in AC collection systems. The OWPP DC collection system architecture used in this analysis comprise of a centralised offshore collection system. Thus the increase in the losses of DC collection systems is mainly contributed by the DC–DC converters.

In [25], technical and economic assessment of four proposed DC offshore collection grids were analysed, aiming to determine its cost-effectiveness when compared to conventional AC OWPPs. DC equipment efficiencies, DC component cost, OWPP rated power, and export cable length were taken as parameters for sensitivity analysis because of the uncertainty of DC technology which may affect technical and economic feasibility of DC OWPPs. Figure 2.4 below illustrates the methodology proposed for OWPP cost analysis. In this analysis also DC offshore collection have been considered for DC collection system topologies. The results show that DC configurations involve higher capital expenditures and lower cost of energy losses. The cost of DC OWPPs are mainly affected by the cost of wind turbines, DC/DC converters and platforms, as well as the energy losses cost of such DC/DC converters. Therefore, both cost reduction and efficiency improvement of the electrical components of the DC OWPP (specially DC/DC converters) are required to make this option still m

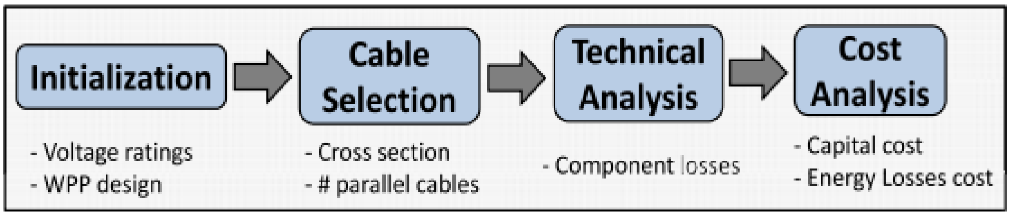

Figure 2.4 General flowchart of the methodology proposed for OWPP evaluation [25]

2.4 DC Collection System Protection

In order to realize the continuity and security of transferring a high level of wind power into an electrical network, the grid codes have been issued for the grid-connected wind turbines or wind farms [26]. However, all of the existing grid codes for wind turbines are almost established for ac systems, and there are rarely grid codes for dc transmission and collection systems of the wind farms.

The handshaking method is proposed in [27], which can locate and isolate the faulted dc line and restore the dc system without telecommunication. The protection for the low-voltage dc system is discussed in [28], where the modern voltage-source converters are considered as fast-acting current-limiting circuit breakers (CBs). The fault characteristic for the dc-grid wind farm is analysed and some possible protection methods are given in [29]. A dc overvoltage control during loss of the converter in the multi-terminal HVDC system is presented in [30]. The DC cable short-circuit fault is one of the most serious disturbances of the HVDC transmission systems, which may paralyze the entire offshore wind farm. Therefore, a dc-grid offshore wind farm must have the ridethrough capability. However, the fault ridethrough issue of dc-grid offshore wind farms under a dc transmission cable fault has not been mentioned in relevant grid codes and literature.

The redundancy operation approach is presented in [31], where the faulted cable can be isolated through the actions of the corresponding switchgears. The offshore wind farm power can be sent to the grid with the healthy cable. Fault ride through control is proposed for the offshore wind farm, where a centralized controller generates the upper limit power demand for each wind turbine. Consequently, the dc-grid offshore wind farm can still operate under the HVDC link faults without wind turbine shutdown, which can make full use of the capacity of the healthy cable and send as much power as possible to the grid.

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3. Review and evaluation of OWPP control systems

3.1 Introduction

The objective of this document is to look into the control of the offshore wind power plants connected by voltage source converter based high voltage direct current transmission (VSC-HVDC) in detail. As explained in Chapter 1, VSC-HVDC is a technically preferred solution for the connection of offshore wind power plants (OWPPs) to the shore. It is intended to further develop better understanding of the challenges faced in the power system integration of VSC-HVDC based OWPPs.

Traditionally, the main aim of the wind turbine control (WTC) is to ensure energy production by the WT at the lowest possible cost, which means that the WTC aims at maximum possible power (MPP) production, limited only by the rated power of the WT [1]. Additionally, the WTC also aims to reduce the structural loads, effectively reducing the costs of the mechanical components and thus contributing to reduction of cost of energy production [1]. Finally, in order to secure quality, stability and reliability, and reduce the required grid connection costs, the WTC also aims to improve the integration of the WTs in the power system [1].

The main aim of the advanced offshore wind farm controllers has been to meet grid integration challenges [1]. With limited, distributed installations, the main grid integration concern has been the influence of the power quality of the wind turbines on the voltage quality in the local grid. However, large wind power installations also influence more system related issues such as power and frequency control, reactive power and voltage control on the transmission system level, and the reliability and stability of the power system [1].

3.2 Challenges

The backbone of a multiterminal HVDC grid realization is the control strategy of the interconnected power electronic converters. The control strategy should ensure that the system can remain stable during unexpected events e.g. faults on the AC or DC side of an HVDC grid or a station disconnection.

In HVDC grids, the maintenance of the DC voltage within strict limits is required for the protection of the equipment and the minimization of losses. As a result, droop controlled stations which conform to this rule have conventionally such a droop curve slope that for small deviations in DC voltage, a great variation of power is allowed, sacrificing the accurate power flow. A challenge is to design droop control mechanisms that prioritize on power flow requirements, retain the DC grid voltage close to its nominal value and still offer acceptable dynamic response during fault events or power scheduling changes [2].

Another control challenge appears in the connection of multiple stations on an AC islanded grid, such as a large offshore wind park. When a single station is connected to an offshore grid, the control strategy is simple and essentially sets an AC voltage which the wind turbines follow. The size of an offshore grid can be so large that multiple stations need to be connected to it and share the transfer of the produced power. In this case, special strategies must be followed where these stations simulate the connection of multiple synchronous generators on a typical AC grid, without the stations communicating with each other.

The implementation of large scale offshore grids will happen only if reduced cost of offshore WPPs will be achieved, (ii) at the same time offshore grids may help lower the total cost of wind power and (iii) active support from WPPs to the operation and control of offshore grids can boost their chance to eventually be built [3].

For services directly regarding the dynamics of the DC part of the offshore grid, the available contribution from WPPs is more limited. This is due to the much faster dynamics in DC networks than in AC grids [4]. Looking at state-of-the-art WPPs, it seems unlikely they would be able to provide the needed support during e.g. the first instants after loss of an onshore converter station. For this, supplementary storage devices or added contribution from other onshore stations may be needed, while WPPs can take over as the system approaches steady-state again. This issue will be particularly critical if the amount of wind generation compared to the size of the offshore grid will be very significant.

Another aspect that is worth mentioning is how to integrate WPPs from different developers and manufacturers and one or more offshore HVDC converters in offshore AC islands. The inertia-less nature of the network gives more control freedom but also poses possible new challenges to guarantee stability, due to converter interactions. At the same time, the proximity of WPPs from different vendors is a factor that must be taken into account in the design and tuning phase. Some work has been done on the issue, e.g. [5], but more research is needed to offer complete and robust treatment of the topic.

3.3 Wind power plant model and control

The WPP consists of the following:

- A number of wind turbines connected to the point of common coupling (PCC) through a transformer
- A Wind Power Plant Controller (WPPC)
- Measurement devices for voltage, frequency, current, power at PCC

The block diagram of the basic control architecture of the WPP is shown in Figure 3.1 [6].

3.4 Wind turbine Model and Control

The wind turbine model, shown in Figure 3.2, is described in [6]. The control functionalities, at the wind turbine level are the optimal speed reference, the power reference selection and the estimation of available power are described in this section.

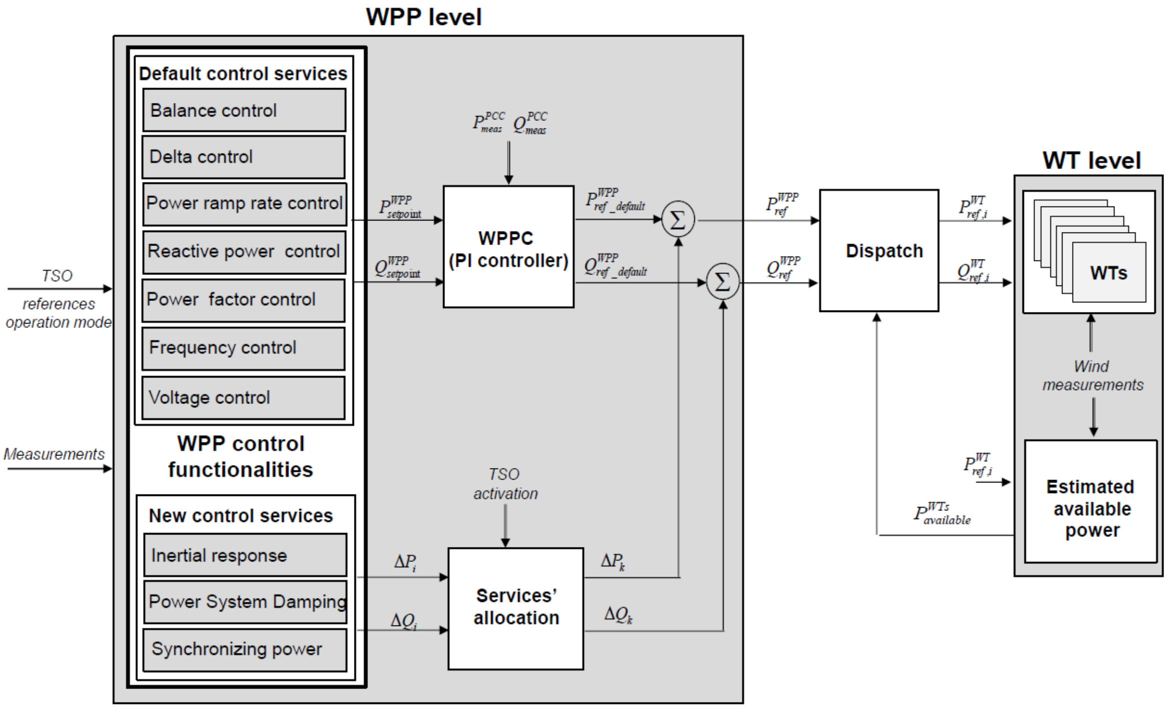

Figure 3.1 Overview of the Wind Power Plant control architecture [6]

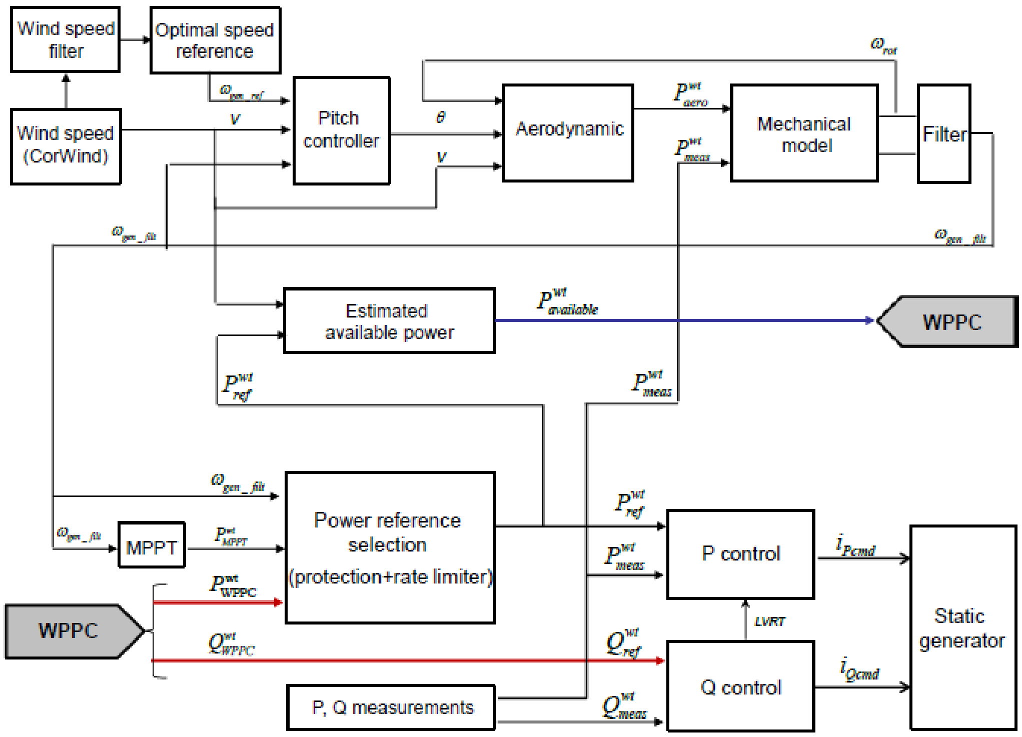

Figure 3.2 Overview of the Wind Turbine Model [6]

WTC has two main objectives: protection and optimization of operation, while having to cope with the highly variable, intermittent and unpredictable nature of the wind [7]. To this end, all WECS have some sort of power control – passive/active stall with passive leading to unacceptable levels of mechanical loads while active extends the control objectives to increase the power capture, thus optimizing the WECS operation [7]. Fixed-speed WTG, with either passive or active stall, dominated the wind power industry for a long time, but disappeared with the use of DFIG-based WTG due to absence of control flexibility. Now variable-speed (VS) WTs incorporating full scale power converters (PEC) are taking over as they allow optimal operation at varying speeds unlike FSWTs [7][8].

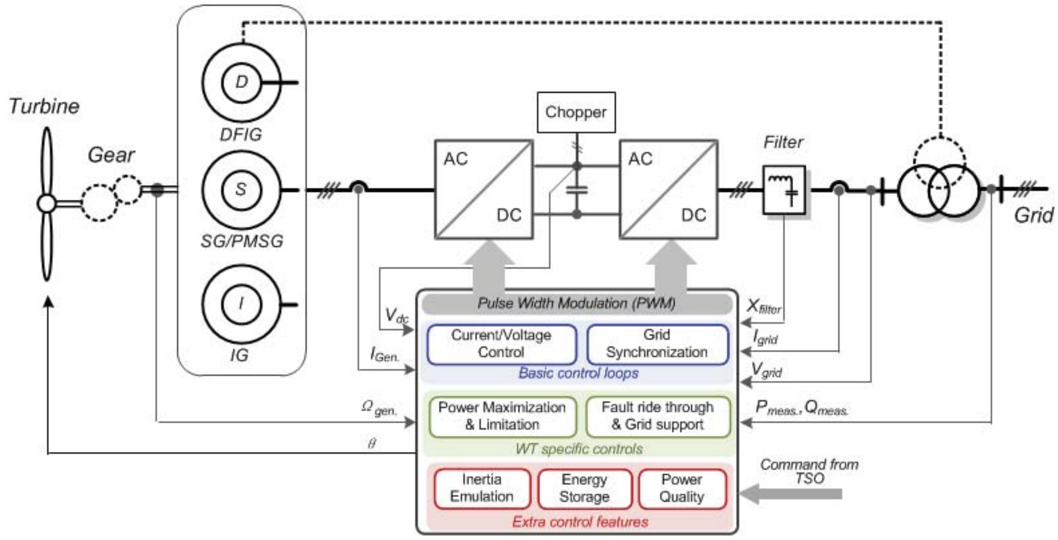

Figure 3.3 WTC structure and objectives [8]

The VSWT control system consists of aerodynamic power control through pitch control, variable-speed operation & energy capture maximization, by generator control, and grid power transfer control using the PEC. Figure 3.3 shows the general control structure for modern WTs.

The WT aerodynamic power conversion efficiency is governed by the power-coefficient C_P which varies with the tip ratio $\lambda = \frac{\Omega R}{v}$, where Ω is the rotor speed, R is the blade length and v, the wind speed. As shown in Figure 3.4, the power-extraction efficiency is maximum for a λ_{opt}, thus as the wind speed varies, the rotor speed must be varied for maximal efficiency energy capture.

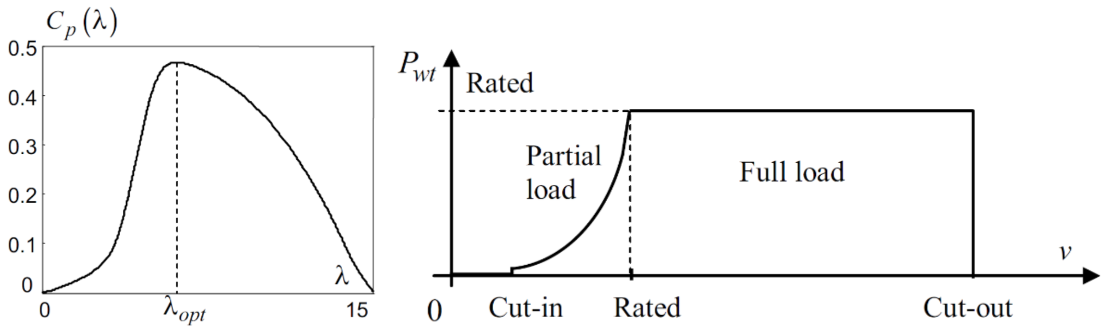

Figure 3.4 WT Performance curve [7]

The WT output power evolves proportionally to the wind speed cubed), until it reaches the WT rated power at *rated wind velocity*, which splits the WT operation range in two: below rated (also called partial load region) where the maximum possible power (MPP) should be produced, and full load region, where the captured power must be limited to rated [7]. The WTC thus adjusts the WT production to the power reference imposed by the TSO, which in normal conditions is the MPP, while in the power-limitation regime is either rated power or less, as shown in Figure 3.5.

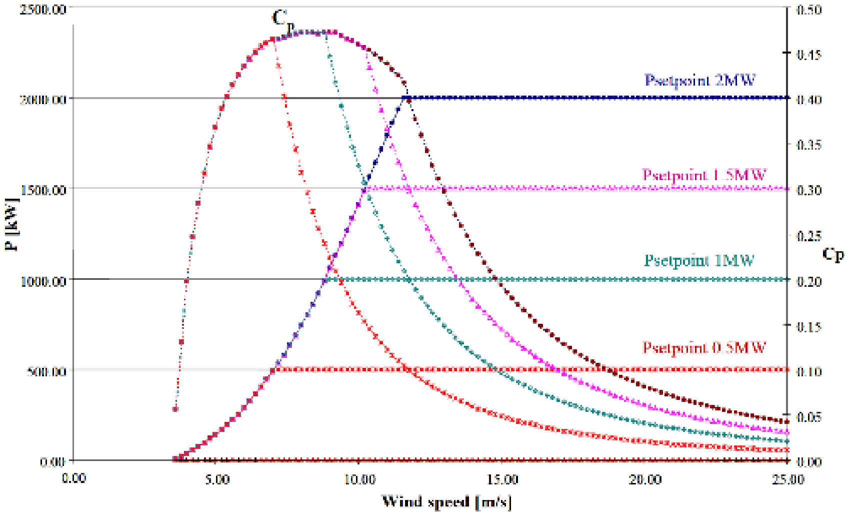

Figure 3.5 Power curves and Cp curves for a 2 MW active stall wind turbine for different imposed power set-points [1].

The control subsystems have different objectives in the different operating regimes as shown in Figure 3.6.

In the non-connected zone, the delivered power is zero and the main objective is to set the generator speed to a constant value $\omega_{G,min}$ with pitch angle defined by optimal pitch angle curve as shown in Figure 3.6 [9].

In the partial load regime (low wind speed & transition zones), the pitch control system is typically inactive except when used to assist start-up and limit rotational speed as wind speed approaches rated value [7]. Thus, the blade pitch angle is set to a minimum to capture maximum energy or limit the rotational speed to rated [9]. The generator control is the only active control and aims at maximizing the energy captured from the wind and/or at limiting the rotational speed at rated by continuously accelerating or decelerating the generator speed in such a way that the optimum tip speed ratio ($\lambda_{opt} \rightarrow C_{P,max}$) is tracked for $P_{G,opt} = K_{opt}\omega^3$ [7][9]. For the transition zone, the demanded electrical power is a suboptimal solution with regard to the delivered power, however by managing the delivered power (and indirectly the generator torque) the generator speed is set to rated values [9].

In the high wind speed zone, a closed loop speed control using variable pitch sets generator speed to rated value, so that the WT keeps both rated speed and rated power under wind speed fluctuations at high wind [9]. The pitch control limits the aerodynamic power to the rated one and, when the wind speed reaches the cut-out value, to stop the wind turbine, thus alleviating the mechanical loads on the WT structure [7].

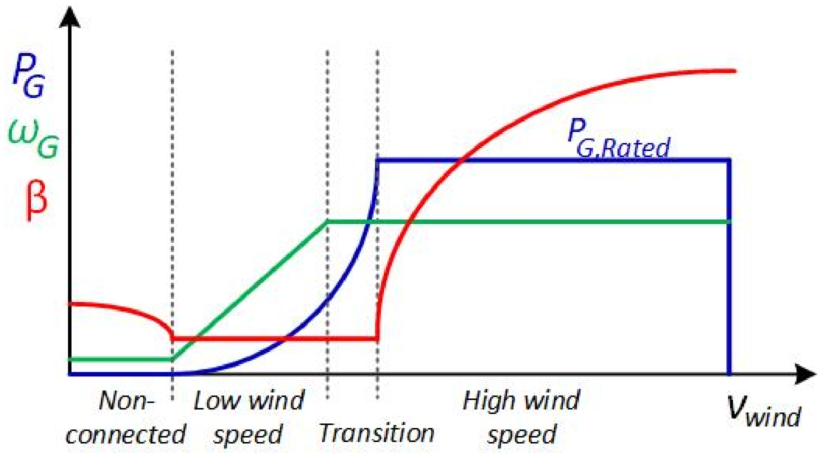

Figure 3.6 Generator speed & power and Pitch angle in the different control zones [9].

Note however, since the generator control deals mainly with the power conversion efficiency optimization, sometimes this means that the generator torque varies along with the wind speed and can induce supplementary mechanical stress to the drive train [7].

3.4.1 Control of Wind Turbine Converters

Recently, the increasing requirements for WTs to remain connected and to provide active grid support have added control objectives for the PEC, such as fault-ride through, voltage/frequency support to the grid, etc. which ensures that the strict power quality standards (frequency, power factor, harmonics, flicker, etc.) are met [7]. The PEC interface of the VSWT consisting of the grid side converter (GSC) and generator/rotor side converter (RSC) is shown in Figure 3.7.

The generator current of the VSWT is changed by controlling the RSC to and thereby the rotational speed of the WT can be adjusted to achieve MPP production based on available wind power. Thus, the generated active power of the WT is controlled by the RSC, whereas the reactive power fed into the grid is controlled by the GSC, while maintaining the DC link voltage for power balance [8]. During grid fault, coordinated control of the different WT subsystems like RSC/GSC, braking chopper/crowbar and pitch angle controller are necessary [8]. Finally, the basic/lower-level controls such as current regulation, DC bus stabilization, and the grid synchronization are performed with higher bandwidth using proportional-integral controllers [8].

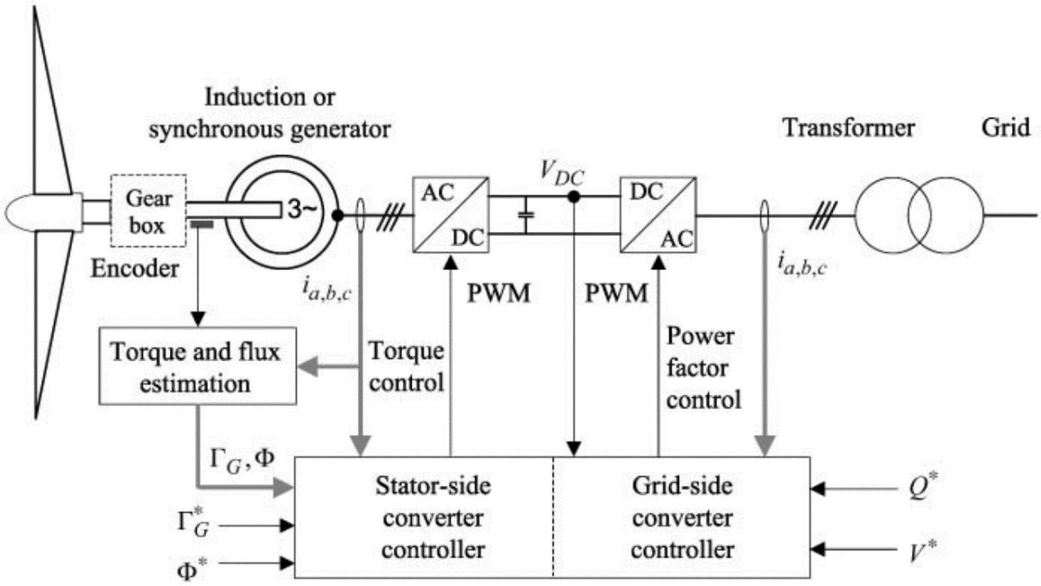

Figure 3.7 Variable speed WT with full-scale PEC [7]

RSC is controlled using an indirect rotor-flux-oriented dq control due to its simplicity, in which the stator current controls the flux (q-axis) and the torque (d-axis) [7]. MPP extraction control sets the torque reference while the rotor magnetizing current reference is a function of the rotor speed or, for simplicity, can be kept constant [7]. The control consists of a cascade structure as shown in Figure 3.8, with a very fast (high bandwidth) inner current-control loop & a slower outer power-control loop, and the output of the current controllers is the pulse-width-modulation (PWM) factor, Pm that controls the converter operation [7].

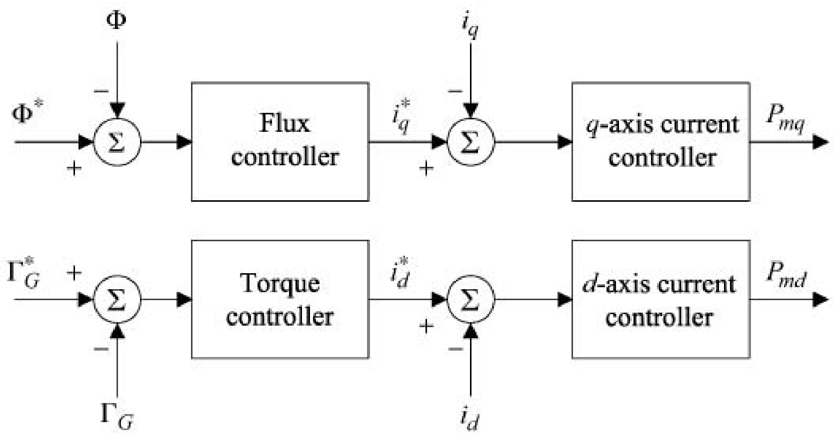

Figure 3.8 VSWT RSC control structure [7]

The GSC is controlled to keep the DC-link voltage constant while ensuring the quality of the output voltage and current in accordance with the standards, usually operating at unity power factor [7]. Similar to the RSC control, the active and reactive components of the grid-side converter currents are controlled by a very fast inner control current loop, while the DC-link voltage is controlled by a slower outer control loop that defines the q-axis current component set-point, as shown in Figure 3.9.

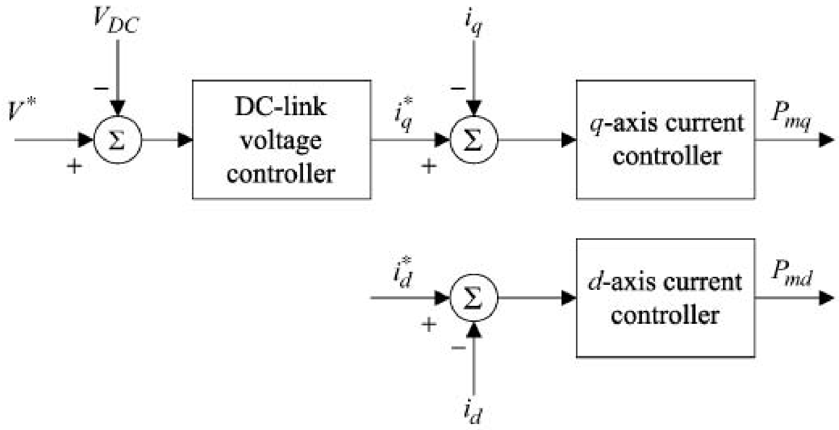

Figure 3.9 VSWT GSC control structure [7]

3.4.2 Optimal speed reference

The reference speed for the pitch controller is derived based on an “optimum speed” look-up table as a function of the wind speed. It facilitates in activating the pitch controller in an efficient way.

3.4.3 Power reference selection

The active power reference of the active power control loop $P_{ref}^{\omega t}$ is generated internally in the variable speed wind turbine (VSWT) based on:

- signal from the maximum power point tracking (MPPT) lookup table
- active power reference $P_{MPPT}^{\omega t}$ from the WPCC
- Wind Turbine rotational speed (ω_{gen})

A rate limiter for the power reference is also included. This is shown in Figure 3.10 [6].

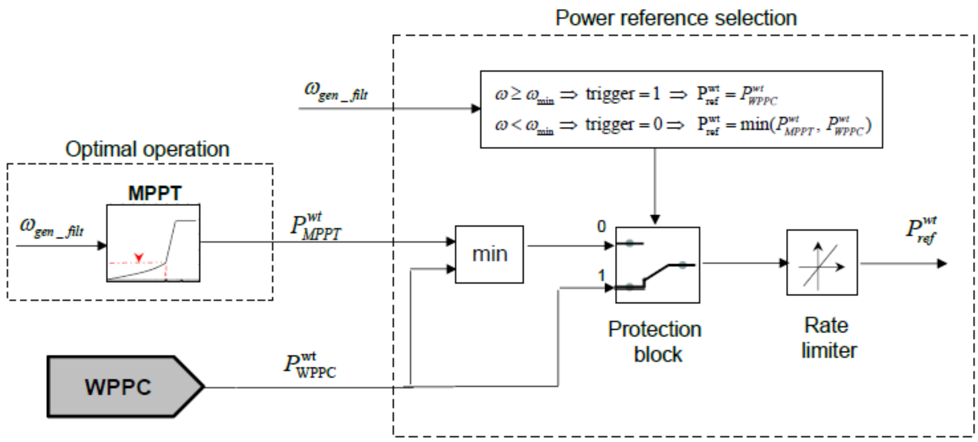

Figure 3.10 Power reference selection [6]

3.4.4 Estimation of available power

The available active power $P^{\omega t}_{available}$ is the optimum value of active power available from the WT without the curtailed operation. A wind speed time series, generated by a wind speed generator programme (i.e. CORrelated WIND power fluctuations model [9]) is fed through the turbine optimal power curve, followed by a first-order filter. Figure 3.11 depicts the inputs and outputs of the estimation of available power algorithm schematic [6].

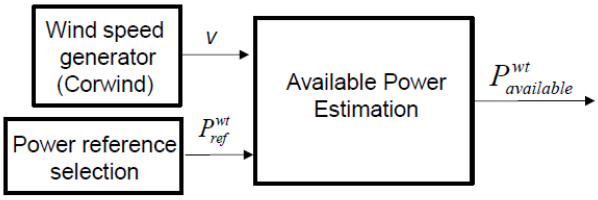

Figure 3.11 Estimation of available power [6]

3.5 Wind power plant – control functionalities

The different control features and services, which are required today by grid codes [3] and system operators, have been implemented at the WPP level, such as:

• **Balance control** (absolute power de-rating) by means of which the WPP production can be adjusted (increased or reduced), in steps at certain constant levels.

• **Power ramp rate control** by means of which the rate of change of active power production can be controlled.

• **Delta control** (power spinning reserve) by means of which the WPP is ordered to operate with a certain constant reserve capacity with respect to its momentary possible power production capacity.

• **Reactive power control** controls the reactive power in PCC, i.e. WPP is able to produce/absorb a constant specific amount of reactive power.

• **Frequency control** (governor characteristics) controls the frequency in PCC, i.e. WPP produces more or less active power in order to compensate for a digressive behaviour in the frequency.

• **Voltage control** controls the voltage at PCC, i.e. WPP is able to generate/absorb reactive power to/from the grid in order to compensate the variations in the voltage at PCC.

The fault ride-through (FRT) capability has also been implemented in the WT level [10].

The WPPC is an outer (slow) control loop in the WPP control structure. It consists of two control loops, one for the active power control and the other for the reactive power control [7]. The inputs to the WPPC are the measured active and reactive powers (P^{PCC}_{meas} and Q^{PCC}_{meas}) and the power setpoints ($P^{PCC}_{\text{setpoint}}$ and $Q^{PCC}_{\text{setpoint}}$) generated based on the controller outputs (P^{PCC}_{demand} and Q^{PCC}_{demand}). This is illustrated in Figure 3.12.

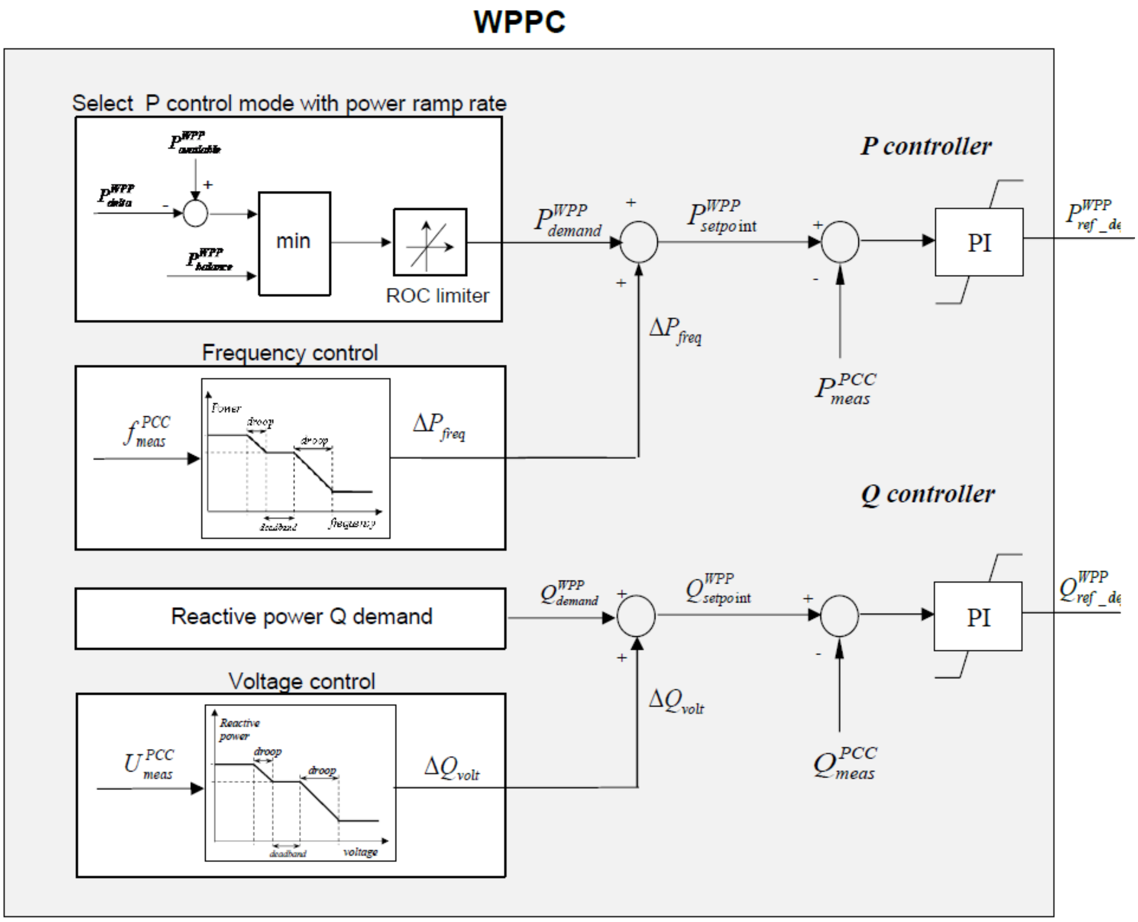

Figure 3.12 Wind power plant controller with the control services [6]

Each loop consists of a PI controller that has an anti-wind-up to ensure a proper power production from the WPP. The frequency and voltage controllers compute an active and reactive power errors respectively and sets up the power reference for the whole WPP.

The WPP also provides control functionalities for new ancillary services, namely Inertial Response (IR), Power Oscillation Damping (POD) and Synchronizing Power (SP).

3.5.1 Inertial response (IR)

Figure 3.13 [6] represents a potential inertial response (IR) controller in a WPP. Whereas existing inertia responds immediately to ROCOF (df/dt), the IR controller will respond after a delay of a few line periods. The IR controller also responds to the frequency error Δf in a way similar to that by a conventional speed governor to provide frequency containment reserves. The grid frequency is measured through a PLL (Phase Locked Loop). The output of the IR controller ΔP_{IR} is the calculated inertial response (delta active power) in pu.

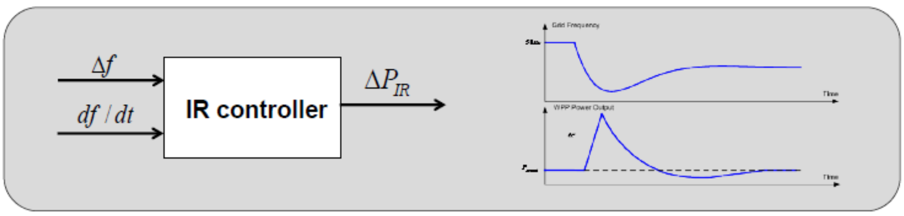

Figure 3.13 IR controller and input/output waveforms [6]

3.5.2 Power oscillation damping (POD) control

The objective of this control functionality inside the WPP is to illustrate that a WPP can be used as a damping device for the power oscillations observed in a power system - similar to the PSS of synchronous generators. A WPP may be used as a damping device by modulating either active or reactive power output [11].

The input of the POD controller is the actual signals, the current magnitude and active power flow while its output is a delta (modulated) signal, as shown in Figure 3.14 [6]. As stated earlier, the WPP can provide POD support by modulating either active and/or reactive power, i.e. ΔP_{POD} and ΔQ_{POD}.

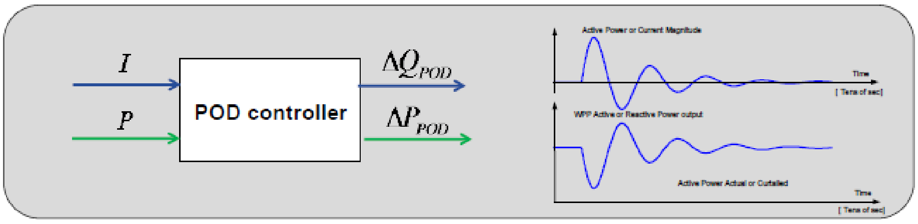

Figure 3.14 POD controller and input/output waveforms [6]

3.5.3 Synchronising power (SP) support

SP is an in-built feature of synchronous generators (SGs), which reduces the load angle between groups of SGs in the power system. If the load angle is allowed to go too high, the SGs may lose torque and system becomes unstable. An increase in the share of converter connected generators, as the case of WPPs, decreases the amount of the available SP in the system. The idea of SP as a new ancillary service from WPP, is thus to improve the steady state stability of the power system by giving additional power into the system from the WPP, in case the rotor angle increases above a prescribed safe limit. Based on the rotor or voltage angle deviation the SP controller increases the active power output of the WPP and thus balance the lack of SP in the system.

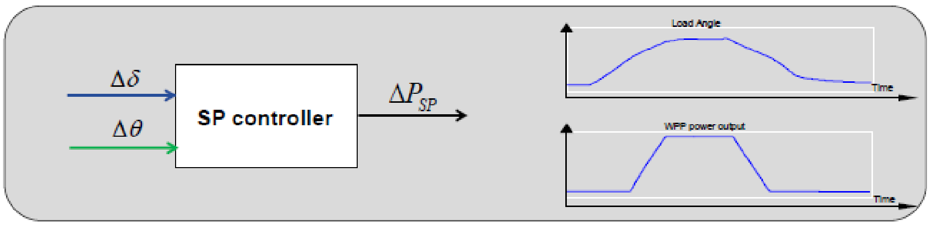

Figure 3.15 SP controller with the input/output waveforms [6]

As illustrated in Figure 3.15 [6], two different input signals are investigated i.e., rotor angle difference between 2 generators and the voltage angle difference between 2 busbars.

3.6 Offshore VSC Converter Control

Offshore cluster or hub is an offshore substation that is formulated by connecting several wind power plants at a common node that are at short distance from each other. Offshore side converter acts like a slack source, provides reference frequency to the offshore network and controls the voltage magnitude at the reference bus [13]. The control of offshore AC islands connected with VSC-HVDC technology relies on power electronic devices and if Type 4 wind turbines are used, the grid literally becomes inertia-less. It could lead to instabilities such as unstable interaction of converters with grid resonances. The offshore HVDC converter controller consists of a standard current controller and a voltage controller as well as an active power droop mechanism [3]. This is shown in a simplified schematic block diagram in Figure 3.16. The active and reactive power droop blocks are essential where multiple HVDC converters are required to share active and reactive power flows.

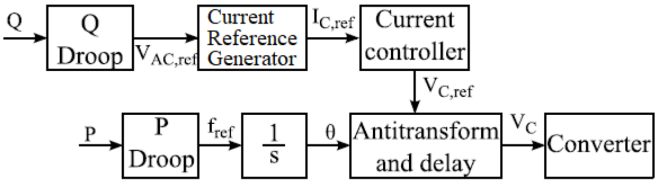

Figure 3.16 Generic offshore HVDC converter control schematic [3]

The reference current generator block shown in Figure 3.16 above can be implemented using different possible schemes. This is discussed in the following sections.

3.6.1 Nested Voltage-Current Control

This control scheme is based on the use of vector voltage control in the synchronous reference frame (SRF) synchronized to the PCC voltage V_{AC}. The reference currents are given by the voltage controller that controls the PCC voltage vector as shown in Figure 3.17. This control loop is followed by a fast inner current controller based on classical SRF frame, which generates the converter voltage references as shown in Figure 3.16. Hence, it is referred to as a Nested voltage-current control scheme [14]. The main advantage of this control structure is that it directly offers current control capability, which is crucial in protecting the power electronic devices in the converter. The reference currents as derived from the control scheme shown in Figure 3.17, can be expressed as:

$$i_{d,ref} = K_p\left(1+\frac{1}{sT_i}\right)\left(v_{d,ref}-v_d\right)-B_C v_q + i_{Ld}$$

$$i_{q,ref} = K_p\left(1+\frac{1}{sT_i}\right)\left(v_{q,ref}-v_q\right)-B_C v_d + i_{Lq}$$

where, B_C is the susceptance of the shunt capacitance connected at the PCC and v_d, v_q are the components of V_{AC} in the SRF. The voltage references are $v_{d,ref} = V_{AC,ref}$ and $v_{q,ref} = 0$.

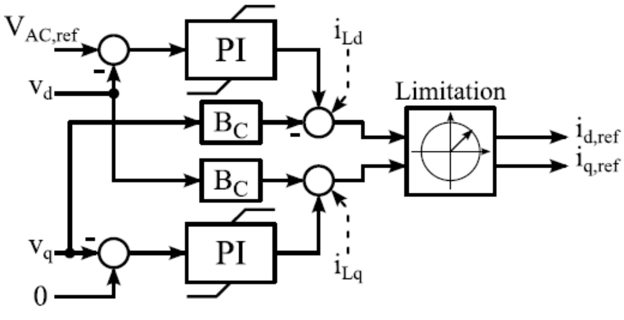

Figure 3.17 Offshore HVDC converter voltage controller (current reference generator block): Nested voltage-current control [3]

The challenge to the design of this controller is posed by the switching modulation delays, at sub-fundamental frequencies since the negative resonance peak, if present, is shifted to the right by the grid impedance and the influence of the delay is unnoticeable. The delay causes instability at negative pulsations as illustrated by the Nyquist plots [3].

3.6.2 Direct Voltage Control

This control scheme as shown in Figure 3.18, is based on a direct integral voltage control action at the PCC [15]. The current dependent terms are added to the control with a proportional gain and zero integral gain to cancel out the effect of the current controller block and be able to make use of the same control structure as shown in Figure 3.16. The voltage control is in the SRF synchronized with the converter voltage. Although it bypasses the current controller in the normal operation, but it offers automatic current limitation at high currents during e.g., faults.

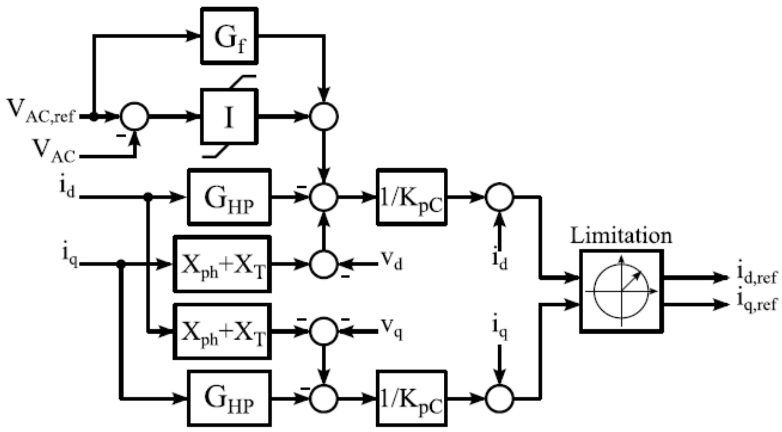

Figure 3.18 Offshore HVDC converter voltage controller (current reference generator block): Direct voltage control [3]

The current controller would therefore be redundant and the converter voltage could be generated directly based on the following control law:

$$v_{Cd} = \frac{K_e}{s}\left(V_{AC,ref} - V_{AC}\right) - G_{HP}(s).i_d + G_f(s).V_{AC,ref}$$

$$v_{Cq} = -G_{HP}(s).i_q$$

where, $G_{HP}(s) = \dfrac{sk_v}{1+sT_v}$ serves as active damping block against grid resonances, $G_f(s)$ is the feed forward transfer function (may or may not be used), K_{pC} is the proportional gain of the current controller, X_{ph} is the phase reactor and X_T is the transformer impedance [3].

3.7 Onshore HVDC Station Control System

The onshore HVDC station controller is depicted in Figure 3.19. The controller is implemented in SRF with the d-axis aligned with the reference voltage at the PCC and generates the current references for the current controller block. The active power control can be performed either by taking the feedback of the active power or by controlling the DC voltage in either closed loop or open loop control. Squaring of the DC voltage is done in order to guarantee linearity between control output and input. Similarly, reactive power can be controlled either by taking the feedback of the reactive power or by controlling the AC voltage in either closed loop or open loop control. The onshore VSC HVDC converter typically provides AC voltage droop by a proportional gain. The contribution of VSCs to the available short circuit power with AC voltage droop control is dependent on the operating point, due to the non-linearity of the gird. For networks with low SCR, operation without AC voltage droop may easily lead to instability for large reactive power variations [3].

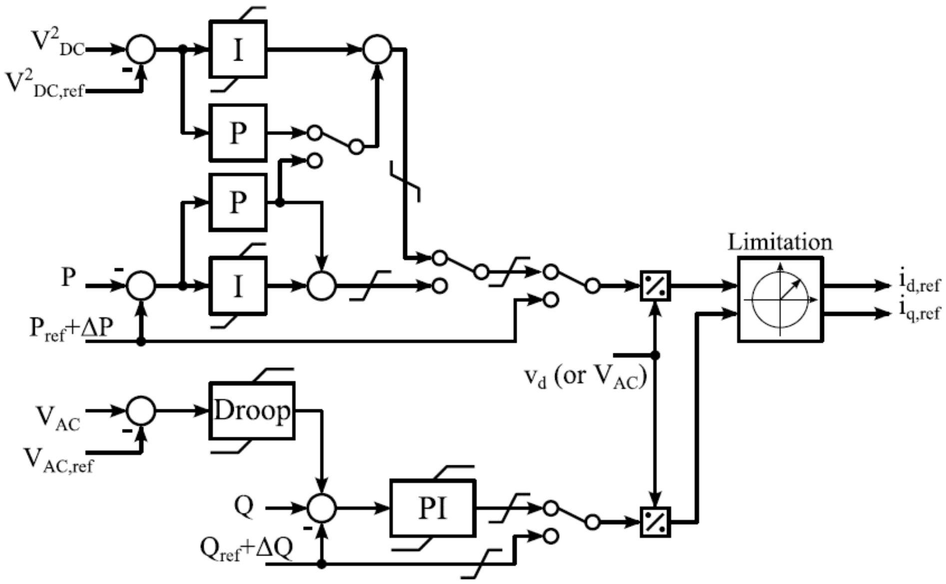

Figure 3.19 Onshore HVDC station controller (current reference generator block) [3]

3.8 Power Balance Control

Active power balance at all times is one of the principal control objectives in power systems. Active power balance control in AC-DC grids can be naturally measured in terms of frequency in AC systems and the voltage in DC systems. Power balance in VSC based DC systems is implemented through DC voltage control [4],[16]. Modern WPPs are expected to contribute to frequency control. But the installation of VSC-HVDC systems and their combination with WPPs raise new issues in relation to (i) how WPPs can contribute to frequency control being decoupled from AC systems by VSC-HVDC systems and (ii) what contribution WPPs can give to DC voltage control in DC grids [17].

3.8.1 AC frequency control

Considering both Inertial Response (IR) and Primary Frequency Control (PFC) through frequency droop, state-of-art WPPs may already provide the necessary support to the onshore grid frequency [18], provided that the sensed onshore frequency can be transmitted offshore with sufficient speed and reliability. There could be two possible schemes to control the frequency (i) communication-based scheme and (ii) communication-less scheme [3]. This is shown in Figure 3.20.

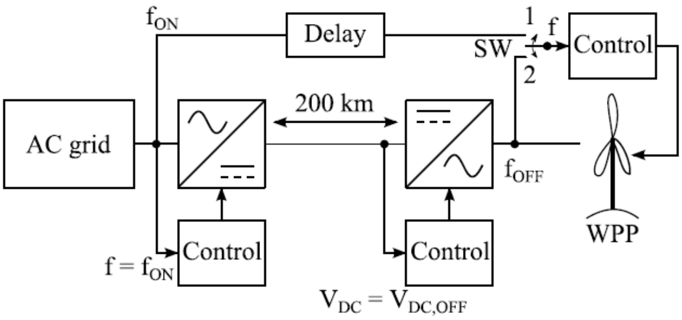

Figure 3.20 Frequency Control provision with OWPPs integrated to VSC HVDC [3]

3.8.1.1 Communication-based scheme

The onshore frequency is directly transmitted to the WPP and its controller (Figure 3.20) by setting the switch SW in position 1. The communication link can be modelled by an ideal time delay, which is expressed as e^{-sT_d} in the Laplace domain. Generally, such delay is a function of the technology used and the number of elements in the communication chain.

3.8.1.2 Communication-less scheme

This scheme makes use of a coordinated control scheme of DC link energy and offshore frequency [19]. The active power droop control for the onshore and offshore stations for this scheme are as shown in Figure 3.21.

(a) Onshore Converter (b) Offshore Converter

Figure 3.21 P-droop block for onshore and offshore converters with communication-less frequency control scheme [3]

The transfer functions for the figure shown above can be expressed as:

$$G_f(s) = \frac{K_f}{1+sT_f}$$

$$G_v(s) = \frac{K_v}{1+sT_v}$$

Due to the initial response of the DC voltage control from onshore HVDC station, the communication-less scheme performs better than the communication based scheme immediately after the event, as supplementary active power is directly evacuated from the DC link so as to decrease the DC voltage and the system does not have to await the WPP response. Perfect mirroring of onshore frequency in the offshore network does need compensation of the line losses. The onshore and offshore frequency curves for communication-less scheme are not very far apart, but using compensation improves the performance. Further, in the presence of large communication delays, communication-less scheme is preferred specially if the ROCOF is a vital element in the system considered.

3.8.2 DC Voltage Control

DC voltage control is actually DC energy control, since the square of the voltage is used as control input. This is done to make the control linear, since the control output is the power is a somewhat more challenging task than AC frequency control. This is true from a static standpoint, as voltage is not a global measure of the power balance in a DC system, contrary to frequency in AC systems. Moreover, depletion of stored energy in a DC system happens in times 2 to 3 orders of magnitude lower than that stored in AC systems SGs' rotating masses. Therefore, DC voltage varies at a much faster gradient than AC frequency does [16].

3.8.2.1 Contribution of VSC HVDC converters to DC voltage control

The excellent capabilities of VSCs for provision of DC voltage control is one of the factors that allows minimisation of their DC link capacitance. Their DC voltage control with PI compensators is usually performed with BWs up to 100 rad/s [14]. DC voltage droop schemes have been proposed for power balance control in multiterminal DC grids [16]. A HVDC converter can act nearly instantaneously in these terms and the overall dynamic response. However, there are a few challenges with VSCs in DC voltage control such as hitting of limits like current capability, DC voltage level, modulation index, cell-capacitor voltage ripple etc., a WPP or a weak AC grid connected at its AC terminals.

3.8.2.2 Contribution of WPPs to DC voltage control

WPPs may pose limitations (depending upon control and communication set up) for services like DC voltage control as it requires very fast control action to ensure proper operation. The DC voltage deviations will have to reach the WPPC by communication or coordinated control means, both options implying atleast some delay. The DC voltage control on the WPP is done as depicted in the WPPC scheme in Figure 3.22. The measurement delays at the WTG level and WPP controller can impoverish the dynamic performance significantly. Feed-forward of the DC voltage control signal (P_{DC}) strongly improves the dynamic response and provides robustness against variations in PI control parameters over WPP's lifetime [3].

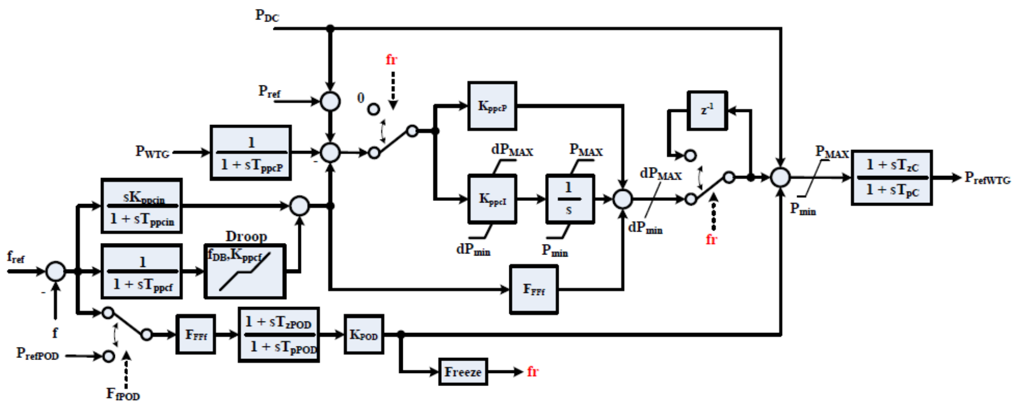

Figure 3.22 WPPC : Active Power Controller [3]

The signal P_{DC} in Figure 3.22 can be generated by a dedicated controller as that depicted in Figure 3.23. Squaring of the DC voltage is done in order to guarantee linearity between control output and input.

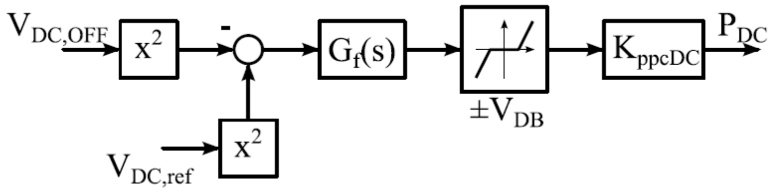

Figure 3.23 WPPC : DC Voltage Controller [3]

3.9 References

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4. Offshore electrical resonance instability

The section of this report describes the resonance instability phenomena taking place in offshore grids. A review of the basic concepts and instability categories used in the literature was carried out. The interactions between the network elements and power converters controllers which are causing instabilities in offshore grids has been studied. Finally, mitigation techniques to reduce the impact of previous identified instabilities are described.

4.1 Introduction

The stability of a network is the capability to remain in equilibrium under normal operating conditions and to be able to return to this state after disturbances [1]. Traditionally, power system stability can be classified as follows:

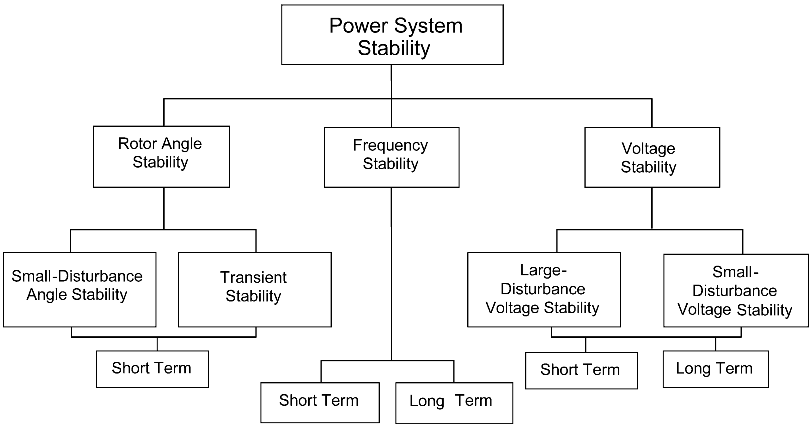

Figure 4.1 Power System Stability Classification [2]

4.1.1 Rotor angle stability

The rotor angle stability is the capability of synchronous generators to maintain or restore the equilibrium between the input mechanical and the output electrical torque, maintaining a synchronous constant speed. A disturbed system causes a generator to spin with a different speed from another, causing the separation of their relative rotor angles. Beyond a certain limit, an increase in angular separation leads to instability [1].

4.1.2 Frequency stability

The frequency stability is the ability of a power system to keep or recover the frequency in a steady acceptable range. Large frequency deviations and a higher rate of change in frequency occur in systems with low levels of inertia. The level of inertia in power systems have been declining due to the replacement of conventional synchronous generators by low-carbon and renewable energies connected to the grid via HVDC transmission [3].

4.1.3 Voltage stability

The voltage stability is the ability of a power system to keep steady state acceptable voltages in all bus voltages. Instability happens when the power system cannot meet the demand for reactive power [4], [5].

The mentioned categories can be further classified based on the size of the disturbance into small and large disturbances. Large disturbances refers to transients events in the systems such as faults, outages, and contingencies; on the other hand, small disturbances are related to minor load and generation changes in the network [2], [4].

4.2 Frequency range stability classification

Energy resources are located in remote areas where the short-circuit ratio (SCR) is small (SCR below 4), named as weak grids [6]. In addition, the circuits are composed by a larger proportion of inductive and capacitive elements compared to resistive ones, such as long length cables and transformers. The interaction of these passive components with active elements has been reported to create resonances [6], [7], [8]. According to the frequency range these instabilities happen, they can be categorized into two large groups: harmonic and near-synchronous oscillations.

4.2.1 Harmonic oscillatory instabilities

High harmonics in the network are caused by instable or marginally stable controllers. Instabilities happen when the frequency of the harmonics is close to the resonance point of the network [9]. These oscillatory instabilities approximately range 0.1 to 2 kHz, and they might damage or reduce the life expectancy of sensitive equipment [8], [6]. Frequent tripping of turbines and converters have also been reported; for instance, the assessment of the harmonic resonance case of two wind warms connected in parallel to the on-shore grid (Figure 4.2) is described in [10]. First, one farm (OWF 1) is connected via two 155 kV cables to the grid via HVDC link. Then, a second farm (OWF 2) is connected to the HVDC station, causing voltage and current oscillations at around 450 Hz. The system becomes unstable and after a few seconds trips. The resonance point was shifted to a lower frequency due to the cable capacitance added at the time of connecting the second wind farm (Figure 4.3).

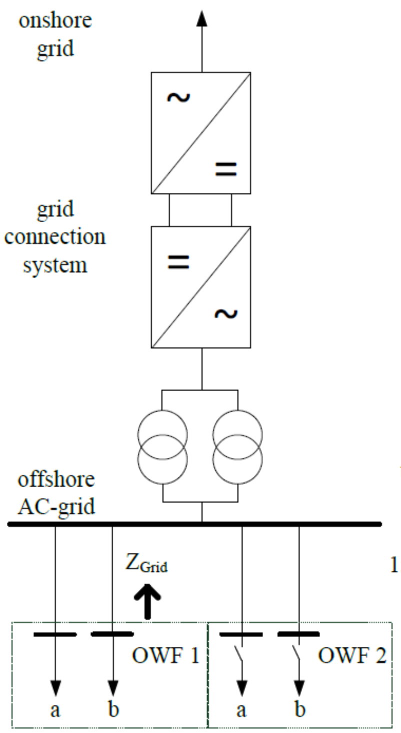

Figure 4.2 Schematic diagram of the HVDC-VSC grid connected Offshore wind farm harmonic stability [10]

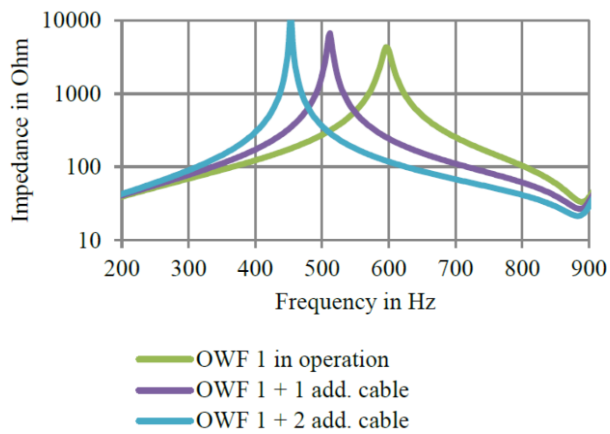

Figure 4.3 Grid impedance seen from the grid connection point [10]

4.2.2 Near-synchronous oscillatory instabilities

These instabilities occur when the electrical network exchanges energy with the mechanical system of generators at one or more frequencies close to the synchronous frequency. However, some instabilities do not involve a mechanical interaction of any kind such as SSCI (Subsynchronous Control Interactions), where the interaction is between the power converter of type 3 wind turbine with series compensated network [4], [11]. According to the range of frequency, near-synchronous instabilities can be further be categorized into super-synchronous and sub-synchronous. Super- synchronous oscillations range 55 to 100 Hz and sub-synchronous oscillations range 25 to 45 Hz [12]. These type of instabilities might cause shaft fatigues and tripping of generators [13], [8].

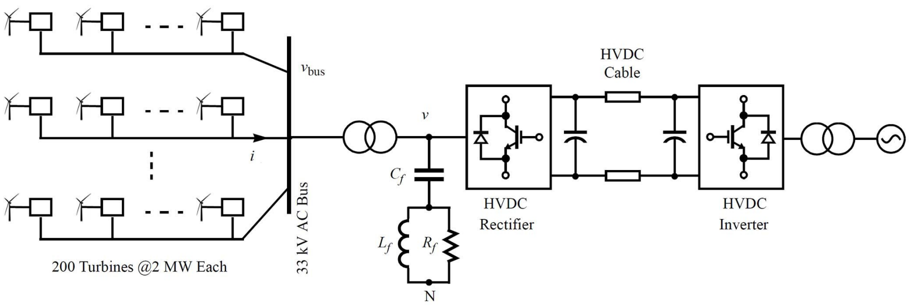

Figure 4.4 Single-line diagram HVDC-VSC grid connected off-shore wind farm [14]

The voltage stability of a off-shore wind farm connected through HVDC (Figure 4.4) to the grid is assessed in [14].The system is simulated for two different control designs and operating conditions. In the first case, the system becomes unstable when the power transmitted through the lines exceeds 60% of the rated power. The voltage and current oscillates at 30 Hz (sub-synchronous). In the second case, the system PLL bandwidth is increased up to 90 Hz and inner controller to 800 Hz. In addition, less capacitance and more inductance in the filter is applied. Oscillations for exceeding 60% occur at 210 Hz (super-synchronous) for this case study.

4.3 Controller design impact

This section describes the impact of the design of HVDC over the system stability reported in the literature. A common control scheme of a VSC converter for controlling disturbances is the two level cascaded controller. The control scheme is illustrated in Chapter 3.

In a cascaded controller, the inner loop must respond much faster than the inner loop for the proper functioning of the system; therefore, there will be enough time for the outer loop to compensate the inner loop disturbances before they propagate. The bandwidth where most components of the converter controller take part is illustrated in Figure 4.5.

4.3.1 Outer control loop

The outer control loop is the primary controller that regulates the operating point of the converter (AC voltage, DC voltage, active and reactive power) by setting a reference point (current references) for the inner controller. The addition of outer loops to the controller structure makes the dynamics of the system non-linear and dependent on the operating point of the converter [13]. In a system with tuned controllers, the non-linear functions introduced to the control become active during large disturbances, leading to negative interactions at subsynchronous frequencies [15].

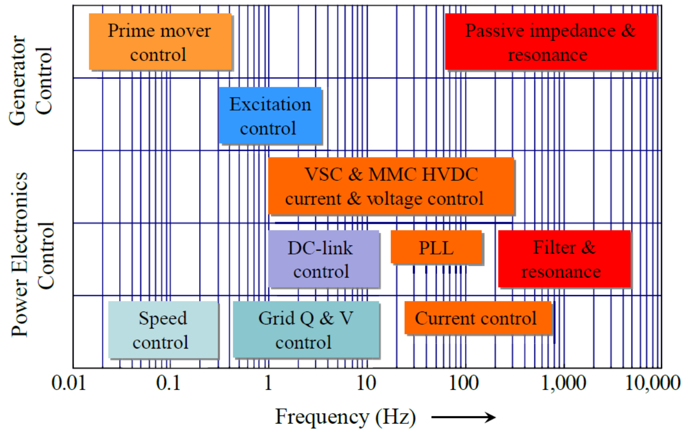

Figure 4.5 Frequency bandwidth of synchronous generators and power electronics for renewable energy and HVDC applications [8]

4.3.2 Inner control loop

The inner loop is the secondary controller. At this point the references set up at the outer loop are controlled at faster dynamics to create new references (voltage references). The dynamic behavior of the inner loop has been studied in [16]. The impact over the output impedance becomes more dominant for a fast inner loop (capacitive equivalent), around 10 ms; on the other hand, the impact becomes less dominant (inductance behavior) for a slower inner controller, around 10 ms, improving the system stability. However, a slow current loop is undesired for a system operating under transients [14].

4.3.3 Switching frequency

High switching frequency in power converters is desired to eliminate switching harmonics. For instance, lower switching requires a large filter inductance to meet the power quality grid require- ments and lowers the bandwidth of the converter controller (inner and outer loop controllers) in VSC PWM (Pulse Width Modulation) modulated converters; however, the switching frequency is limited by the device technology [8] ,[13].

4.3.4 Phase locked loop

The Phase Locked Loop (PLL) is used to determine the angle and angular velocity of the electric network from the voltage positive sequence at the fundamental frequency. The PLL helps to provide a synchronous reference to the power converter controllers. A fast PLL increases the negative impedance zone, degrading the electrical damping at subsynchronous frequencies [13], [17].

4.3.5 Time delay

The time delay is caused by the computation and switching process, and it affects the phase angle of the impedance; therefore, negative resistances can be achieved at high frequencies. It has been studied that time delay have an effect on the harmonic stability [18], [16], [12], [19].

4.4 Mitigation techniques

A mitigation approach is the installation of passive elements to the network to maximize the stability margins in the range of the converter controller bandwidth; however, they are big and expensive at high voltage level, and the space is limited at offshore platforms. What is more, new resonances are generated with every element added to the network [7]. A few techniques studied in the literature to mitigate instabilities are described below.

4.4.1 Active damping

Active damping uses the control advantages offered by VSC converters to maximize the stability margins in a range of frequencies. There are several techniques proposed in the literature. For instance, a second voltage feedforward loop and a notch filter in the PLL dynamics is proposed in [13] to reshape the VSC incremental output impedance and maximize the positive electrical damping at subsynchronous frequencies. About damping harmonic resonances, techniques studied suggest adding a derivate term in the voltage feedforward path, using a virtual resistors in an extra current feedforward loop, and selective harmonic attenuation by notch filters [20], [21], [22].

4.4.2 Tuning of controls

Another approach is to tune the VSC converter controllers, by limiting the bandwidth. The frequencies should be below the network resonance frequency where operating points or switching scenarios can occur. This guarantees that the continuous power infeed coming from converters will not excite grid's resonances or amplify oscillations [23], [15], [7].

4.5 References

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