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Reactive power compensation of the electricity grid with large-scale offshore wind farms in Sweden

Technical capabilities, grid codes and economic incentives

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Abstract

Year 2040 the goal is to have a 100 % renewable Swedish energy system. Svenska kraftnät (Svk) predicts fully decommissioned nuclear power plants and an increased amount of connected wind power plants, especially offshore, year 2045. These kind of renewable power plants are non-synchronous and do not provide the grid with the same system stability services naturally as synchronous generators, such as nuclear power plants. With the increased number of renewables connected, one future challenge is to maintain the stability of the power grid. Grid stability can be divided into voltage-, frequency- and rotor angle stability.

This thesis has investigated how large-scale offshore wind power plants (OWPPs) can contribute with reactive power compensation and in turn voltage stability to a nearby onshore power grid in Sweden. The evaluation has been done from the perspective of the TSO and the OWPP owner interests, with a focus on grid codes, economic incentives and technical capabilities.

This project has been made in three parts. First, a comparison of voltage stability control requirements in different European grid codes were made. Secondly, static power flow simulations of a case study of a 1000 MW OWPP have been performed in PowerWorld Simulator, testing the OWPP's reactive power outputs under different circumstances. Thirdly, a market opportunity analysis has been completed, analyzing reactive power market opportunities for OWPPs as well as for TSOs.

The study shows that the reactive power capabilities of the simulated OWPP is considerable higher than the Swedish grid codes requires. Thus, an opportunity is to make the grid codes stricter, in combination with economic incentives. The case study showed that the distance offshore has an impact of the reactive power reaching the grid onshore. Though, the OWPP's contribution to local voltage stability onshore is considered as good. Finally, with short- and long-term contracts, a reactive power market can be favorable for both the OWPP owner and the TSO.

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Populärvetenskaplig sammanfattning

Klimatförändringarna är en av vår tids mest krävande utmaningar. För att minska klimatpåverkan vid elproduktion har Sverige som mål att skapa ett 100 % förnybart energisystem till 2040, där vindkraften förväntas stå för en stor andel av den totala elproduktionen. I samband med det har den svenska transmissionssystemoperatorn (TSOn), Svenska kraftnät (Svk), fått ett regeringsuppdrag att bygga ut transmissionsnätet till havs, med syftet att öka andelen havsbaserad vindkraft i Sverige. Svk förutser att de nuvarande kärnkraftreaktorerna avvecklas till 2045 och delvis ersättas med vindkraft, både på land men framförallt till havs. Kärnkraft har historiskt bidragit med systemstabilitet, vilken kan delas upp i spänning-, frekvens- och rotorvinkelstabilitet. I ett 100 % förnybart energisystem kan det finnas utmaningar att upprätthålla denna stabilitet.

Det finns två typer av effekt; aktiv och reaktiv. Aktiv effekt är den effekt som transporteras, medan reaktiv effekt används för att upprätthålla spänningsstabilitet. Den här masteruppsatsen fokuserar på spänningsstabilitet och därmed reaktiv effekt. Spänningen fluktuerar på elnätet till följd av att energikonsumtionen varierar under dagen. Spänningsinstabilitet kan delvis orsaka en begränsad överföringskapaciteten på elnätet och att utrustning skadas. Spänningsnivån måste därmed hållas stabil genom reaktiv effektkompensation för att säkerställa ett effektiv och tryggt energisystem.

Det är TSOers ansvar att upprätthålla en trygg elproduktion på transmissionsnätet genom att kontrollera reaktiva effektflöden. Detta genomförs antingen genom krav eller upphandlingar av reaktiv effekt. Dessa upphandlingar kan vara reglerade kompensationer eller budgivning på en marknad för reaktiv effekt. I dag i Sverige styrs reaktiv effekt enbart genom krav, även kallat nätkoder. Det existerar ingen marknad för reaktiv effekt, något som exempelvis Storbritannien visat intresse för. Detta kan komma att förändras i och med det pågående förändrade elnätet, för att säkerställa att tillräckligt med ekonomiska incitament finns för verkägare att bidra med reaktiv effekt. Syftet med masteruppsatsen är därmed att undersöka hur storskaliga havsbaserade vindkraftparker kan bidra med reaktiv effektkompensering för spänningsstabilitet på det landbaserade elnätet. Syftet undersöks ur verkägarens och TSOns perspektiv, med ett fokus på nätkoder, incitamenten och tekniska förmågor.

Undersökningen visar att havsbaserade vindkraftparker kan ha höga reaktiva effektförmågor och bidra med spänningsstabilitet på land. De svenska nätkoderna matchar inte dessa förmågor och det finns därmed en möjlighet att ställa högre krav. Högre kravställning måste ske i kombination med incitament. Det kan dock vara mer önskvärt med en reaktiv effektservice på land, då avståndet mellan parken och elnätet på land skapar effektförluster. Slutligen, med kort- och långsiktiga kontrakt kan en reaktiv effektmarknad vara gynnsam för såväl verkägaren som TSOn.

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Agnes Bråve & Sara Särnblad
Uppsala, May 2022

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Abbreviations

AC	Alternating Current
CAPEX	Capital Expenses
DC	Direct Current
DCC	Demand Connection Code
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
EPF	Expected Payment Function
FSC	Full-Scale Converter
GB	Great Britain
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
NC	Network Code
OCS	Offshore Connection System
OPEX	Operating Expenses
OPPM	Offshore Power Plant Module
OTSDUW	Offshore Transmission System Development User Work
OWPP	Offshore Wind Power Plant
POC	Point of Connection
POI	Point of Interconnection
PPM	Power Plant Module
p.u.	Per Unit
RES	Renewable Energy Source
RfG	Requirements for Generators
Svk	Svenska kraftnät
TSO	Transmission System Operator
WPP	Wind Power Plant
WT	Wind Turbine

Nonmeltable

Symbol	Description	Unit
V	Voltage	V
I	Current	A
P	Active power	W
Q	Reactive power	VAr
S	Complex power	VA
R	Resistance	Ω
X	Inductance	Ω
Z	Impedance	Ω
Y	Admittance	S

1. Introduction

1.1 Background and motivation

Climate change is one of our time's most exigent challenges. Efforts are made all over the world, in many ways, to prevent emissions and further environmental damage. One major step for reaching the UN goal, 'Paris Agreement', of dimidiating the emission until 2030 is the transition of the energy systems [1].

The energy system is noticeably changing due to the great impact renewable energy sources (RES) have on environmental sustainability, in Sweden as well as the rest of the world. Since a few years back, 95% of European investments in new capacity are RES [2]. In Sweden, the total amount of RES in the energy mix was 60 % in 2020, 10 percentage points over the goal of reaching at least 50 % RES 2020. The reasons behind the growth are the high taxes on fossil fuels and economic policy instruments which benefit investments in RES [3]. Wind power is the most growing RES in Sweden, with an increase of 9 installed gigawatt (GW) from 2008 to 2020 [4]. The increase is expected to continue, and wind power have the potential to be the second largest energy source in Sweden as early as 2024, behind hydro power [5]. The national transmission system operator (TSO) in Sweden, Svenska kraftnät (Svk), has been assigned by the government to expand the transmission power grid to areas within Sweden's territorial waters in order to increase the opportunities and lower the costs to connect offshore wind power plants (OWPPs) [6]. Due to the future offshore grid expansion, the interest in OWPPs have expanded rapidly – OWPPs corresponding to a total of 500 TWh annual production are waiting to be approved by Svk [7]. To put into context, Sweden has an annual total production of 150-165 TWh today [8].

Svk [9] has developed several potential scenarios for the future needs and challenges of the Swedish power system, of which one of them is called 'Electrification renewable'. The intension with the scenario is to achieve net zero greenhouse gas emissions in 2045. Compared to today, the changing elements are an increase of electricity consumption as well as electricity production of RES, and a decrement of thermal power. Furthermore, in the scenario, primary electricity production in Sweden will be onshore wind power and large-scale offshore wind power along the coasts in the southern parts of the country. A total of 55.3 GW installed wind power, including onshore as well as offshore, can be expected in 2045. Solar power will mainly be built in cities in combination with batteries. Hydropower will remain in the same position as today, yet nuclear power plants will be fully decommissioned until 2045 [9].

Synchronous generators are traditionally an important resource for stability of the power grid. Grid stability can be divided into voltage-, frequency- and rotor angle stability. Voltage stability is provided by reactive power, frequency stability by inertia and rotor angle stability by short circuit current [10]. Current nuclear power plants in Sweden are placed in the southern parts and have a crucial role maintaining stability in those areas [11]. On the Swedish west-coast, two out of four nuclear reactors in Ringhals have already been decommissioned. Svk has replaced these reactive power facilities with a Static Synchronous Compensator (STATCOM), which is a reactive power control technique [12]. According to the scenario 'Electrification renewable', the future power plants in the area will be RESs, which are most commonly non-synchronous. Non-synchronous generators are connected through power-electronics to the power grid. When replacing synchronous generators with non-synchronous, there will conceivably be challenges maintaining the power system stability [11]. However, with the right equipment, control methods and economic incentives to invest in such properties, RES can be expected to have the ability to contribute with reactive power and potentially inertia and short circuit current [13]. This thesis is focusing on reactive power compensation.

The TSO have the responsibility of controlling and securing the supply of production in the transmission power grid, in order to maintain the system as stable as possible [14]. The tools available for the TSO to use is mandatory requirements or procurements, or a combination of the two. The TSO can additionally invest in reactive power control techniques. Requirements, often referred to as grid codes, are necessary for the securement of power plant capabilities. Procurements can, on the contrary, create economic incentives for power plant owners to provide with power system services. The procurement can either be regulated or through bidding on a market [15]. In Sweden no procurement of reactive power is made, thus only grid codes are used for securing stability. In Great Britain and Denmark, on the other hand, grid codes are used in combination with procurements [15]. In Great Britain a market for reactive power is currently being developed [16].

Svk states that the grid codes applicable for non-synchronous generations could be modified in the future in order to cope with a changed power grid and to imitate the behavior of a synchronous generator. At the same time, Svk points out that the need for economic incentives have increased due to the new technology, creating revenues for certain capabilities [15].

1.2 Purpose

Due to the upcoming increment in installed offshore wind capacity in Sweden and the uncertainty of how expansion of RES is made reliable and economically defensible, the purpose of this master thesis is to investigate how large-scale OWPPs can contribute with reactive power compensation to a nearby onshore power grid in Sweden. The evaluation will be from the perspective of the TSO and the OWPP owner interests, with a focus on grid codes, economic incentives and technical capabilities.

1.2.1 Thesis questions

In order to fulfill the aim of this thesis, the following research questions are stated:

- Are the current Swedish grid codes for offshore power plants reasonable for the ‘Electrification renewable’ scenario? Why or why not?
- What reactive power capabilities can be expected from an OWPP?
- What are the possibilities for an OWPP to contribute to local voltage stability of the onshore power grid?
- How can a market for reactive power be designed to be beneficial for a OWPP as well as the TSO?

1.3 Methodology

The method used can be divided into three parts; literature study, simulations and market opportunity analysis.

1.3.1 Literature study

A literature study on European grid codes was made with the aim of comparing Swedish grid codes to grid codes in Great Britain and Denmark. This was done in order to get an idea of how the Swedish grid codes are constructed for offshore power plant modules (OPPMs) and how other nations, with a greater amount of OWPPs, have adapted their requirements. The grid codes evaluated is the ones related to long-term voltage stability. In turn, chosen grid codes were later used for the power flow simulations.

1.3.2 Power flow simulations

A case study was carried out for making static power flow, also referred to as steady-state power flow, simulations based on grid codes and theoretical reactive power capability in order to compare the two with regards to system performance and behavior. Additionally, comparisons were made with a shunt onshore. A fictitious model consisting of one 1000 MW OWPP, offshore connection system (OCS) and benchmark system was developed and used for the simulations in the software PowerWorld Simulator.

1.3.3 Market opportunity analysis

A market opportunity analysis was made to analyze how a market for reactive power can be beneficial for an OWPP and TSO in the future in Sweden. This was made by studying insights gained from previous and ongoing reactive power market developments. The insights were then complemented with an analysis of OWPPs opportunities to participate partly based on the power flow simulations.

1.4 Delimitations

There are several important and interesting aspects to consider when investigating the future power system stability, but due to the limited timeframe of the master thesis delimitations had to be made. The simulations are static only, and no dynamic simulations were made. Furthermore, grid codes in three different countries are compared and the investigated power grid is of 220 and 400 kV voltage level, no distribution grid impact is evaluated.

Moreover, the simulated OWPP is aggregated, hence no internal power flows within the OWPP were analyzed. For this reason, the design of the OWPP is of simple character, making several simplified assumptions.

Lastly, one specific wind turbine generator type, Type 4, is used.

1.5 Limitations

The thesis has been limited by the fact that a scenario in the future of Sweden is investigated. Therefore, assumptions on future developed equipment were made in order to create a model of a fictive 1000 MW OWPP. The same applies for the investigation of the OWPPs reactive power capability. A further limitation was the limited access to information about the transmission grid in Sweden. Thus, a benchmark model of a theoretical grid was used in the simulation instead of a representation of the actual grid.

1.6 Thesis outline

In **Chapter 2 Theoretical background**, theory regarding electrical power systems, voltage stability and wind power systems is presented.

In **Chapter 3 Grid codes**, a comparison is made between Swedish, Danish and British grid codes set according to EU regulation. In this chapter, information about different grid codes related to reactive power compensation for OWPPs is available.

In **Chapter 4 Case study**, a fictive 1000 OWPP are presented with associated connection system and onshore grid system. Theoretical reactive power capability for the specific OWPP is presented and tested for different scenarios in PowerWorld Simulator. The Swedish and GB grid codes as well as shunt compensation are tested for the scenarios likewise. Chapter 4 ends by presenting and analyzing the simulation results.

In **Chapter 5 Market for reactive power**, different market designs are discussed with regard of OWPPs opportunities to participate based on capability and simulation results. The perspective of the TSO is also considered.

The report ends with a concerted discussion of the results, before stating the conclusions of the research.

In this research, Agnes have had responsibility for the grid codes, the dimensioning of the OWPP and the simulations. Sara have had responsibility of the formation of the connection system as well as the market part. Nevertheless, it is of great importance to state that all of the parts have been made in continuous discussion between the authors. Thus, the authors are jointly responsible for all the parts of this report.

2. Theoretical background

In the following chapter, theory covering electrical power systems, voltage stability and wind power plants is presented. More precisely, Section 2.1 covers the foundations of alternating current, active and reactive power and cables. Section 2.2 describes voltage stability and thereby the importance of reactive power and different reactive power control techniques. Lastly, Section 2.3 examines wind energy conversion, full-scale converter and its reactive power capability.

2.1 Electrical power systems

2.1.1 Alternating current (AC)

The current flow in power systems can either be described as direct current (DC) or alternating current (AC). DC implies when the electric change is only flowing in one direction, meanwhile with AC the flow of electric change is periodically reversing direction. AC means that the current and voltage is variating as sinus-curve along time. In AC systems there are both active and reactive power and in DC systems there is only active power. However, it is theoretically possible with a zero reactive power exchange in AC systems [10].

2.1.2 Active and reactive power

As mentioned, in AC systems the power flow is the flow of active (P) and reactive power (Q) in a network. Active power is the energy transported and reactive power is used to keep the voltage in a stable range in AC systems. Moreover, active power is flowing from high to low voltage angle and reactive power is flowing from high to low amplitude of voltage. These different types of power are calculated from complex power (S), according to equation (1).

$$S = VI^{*} = VI\angle\varphi = P + jQ \tag{1}$$

Where V is the voltage and I^* is the conjugate current. Furthermore, the phase angle, φ, is the angle between the voltage and current. The term cos (φ) is entitled as power factor and is defined as equation (2).

$$cos(\varphi) = \frac{P}{|S|} = \frac{P}{\sqrt{P^2 + Q^2}} \tag{2}$$

$|S|$ is the magnitude of the complex power and termed apparent power. Moreover, depending on the value of the phase angle, φ , the relationship between complex, active and reactive power is different. The power triangle in Figure 1 is showing this relationship.

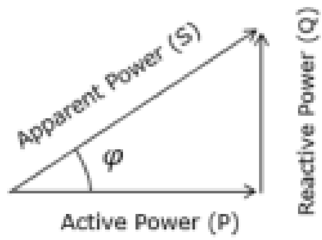

Figure 1. Power triangle.

The power triangle is showing whether the power factor is leading or lagging. When the phase angle is negative, the power factor is leading, and the load is capacitive. Reactive power is then being produced by the load. When the phase angle is positive, the power factor is lagging, and the load is inductive. Reactive power is there for being consumed by the load [17].

2.1.3 Cables

To transport power from the power plant to the consumer, overhead lines or underground cables are used. The main electrical difference between cables and lines is that cables have a considerable higher capacitance. Due to the high capacitance, the current requires to be higher, which can limit the amount of active power being transferred for a given length of the cable. One of the main aspects when determining cable designs is therefore the required current capability capacity which corresponds to the cross-section of the conductor. Conductors are the materials or substances allowing the current flowing thought [18]. The π-eqivantent in Figure 2 is showing the consisting elements in a cable, where the constants resistance (R), inductive reactance (X_L), impedance (Z) and admittance (Y) are included.

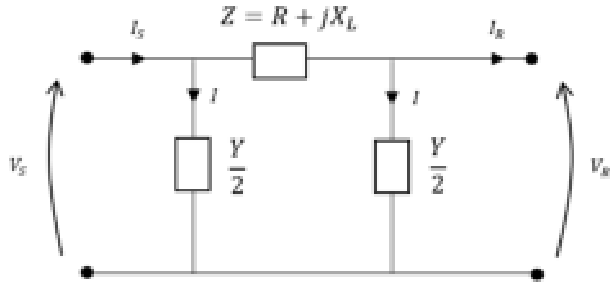

Figure 2. π-eqivantent for a cable.

V_R and I_R are the receiving side voltage and current, V_S and I_S are the sending side voltage and current. In order to improve the power system and discover disturbances on the grid, the power flow or voltage fluctuations through a cable can be analyzed. This can be done by using the cable constants and calculate the ABCD parameters [17], as equation (3).

$$\begin{bmatrix} Vs \\ Is \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} * \begin{bmatrix} Vr \\ Ir \end{bmatrix} = \begin{bmatrix} \frac{Y}{2}Z + 1 & Z\left(\frac{Y}{4}Z + 1\right) \\ Y & \frac{Y}{2}Z + 1 \end{bmatrix} * \begin{bmatrix} Vr \\ Ir \end{bmatrix} \tag{3}$$

2.2 Voltage stability

[19] is defining the stability of an interconnected power system as “the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.” An interconnected power system is including the transmission system and all connected generators which have an impact on the grid. The stability of the power grid is further divided into voltage, frequency and rotor angle stability [19], as seen in Figure 3.

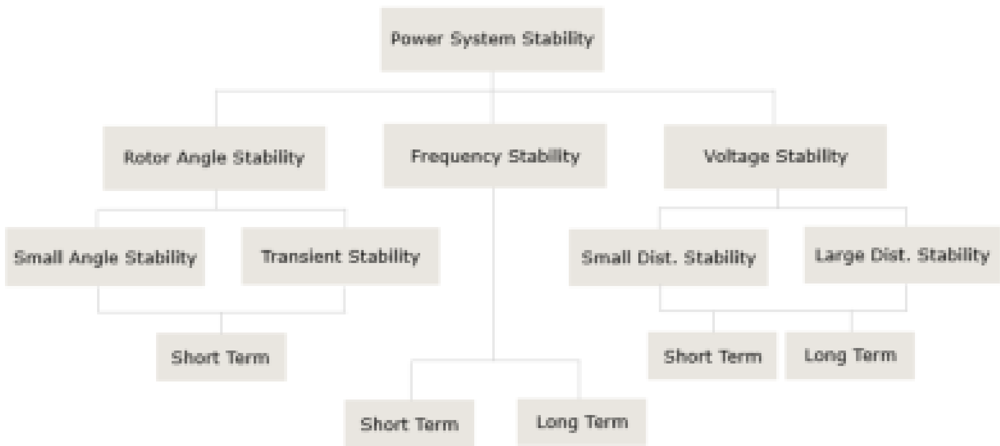

Figure 3. Classifications of power system stability.

As the aim of the thesis is to investigate voltage stability, this part of the power system stability will be further explained. In an interconnected system the voltage is dependent on the local system elements and can therefore only be controlled locally. To keep the voltage stable after a disturbance, reactive power compensation is used [18]. Additionally, the power system must maintain stability between the initial operating condition of load demand and supply after a disturbance. Voltage instability can result in the loss of load and tripping of transmission lines which in turn can lead to cascading outcomes [20]. Figure 3 shows how voltage stability can be divided into small and large disturbance stability. Small disturbance can be due to a load rising by a small amount and as a response, the system must have the ability to keep the voltage within the acceptable range. Large disturbance, on the other hand, can be a loss of a generator, short circuit or system failure, and then the system is kept in stability by keeping the bus voltage within the acceptable voltage range. Moreover, voltage stability is divided in short and long term. Short term voltage stability is lasting in a few seconds, meanwhile long-term voltage stability could last several minutes [21]. Figure 4 shows how the need of reactive power compensation and voltage stability differ over time.

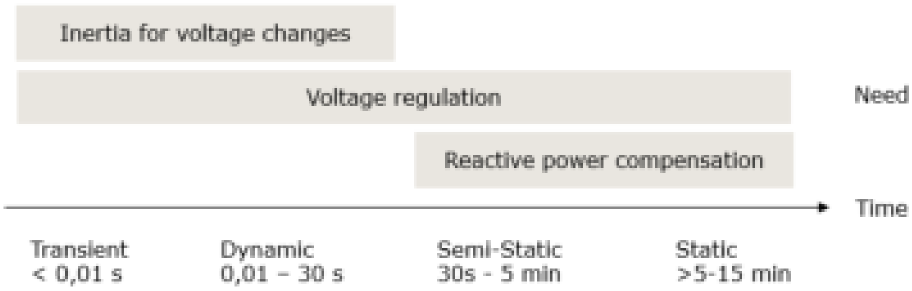

Figure 4. Timeline for the power systems needs regarding reactive power and voltage.

2.2.1 The importance of reactive power

The energy consumption and production vary over the day, which results in the voltages around the loads fluctuate as well. During low load conditions, the voltage is high and vice versa. Many types of equipment work poorly at low voltage [22] and causes decreasing net transfer capacity in the system [23]. At high voltage, equipment can be damaged and their lifetime hence shorted. In order to control the voltage and thereby maintain the power systems reliability and security to maximize the efficiency, reactive power compensation is used. By decreasing reactive power, the voltages reduces and by increasing reactive power the voltage rises. For instance, when the load is high, the transmission line absorbs reactive power and lower the voltage. In this case the transmission line is inductive. At the opposite case, when the load is at a low level, the transmission line act as capacitors and generates reactive power and therefore higher the voltage. Moreover, reactive power must be compensated because of the fact that reactive power production can limit the generator's active power production capability. Additionally, the reactive power flow can affect the amount active power that can be transferred in the transmission lines [22].

Reactive power control techniques
Different types of equipment in a transmission system can control the reactive power in various ways, for instance Synchronous machines, Shunt Capacitors and Reactors, Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM).

Firstly, a synchronous machine is either a motor or generator and its ability of reactive power support is depending on the active power production. If a larger amount of reactive power is produced, less active power can be generated [22]. A synchronous condenser is a synchronous motor and can operate at no load and by controlling its excitation current it is able to act as an inductor or a capacitor. It can thereby provide fast response of reactive power control [24]. Moreover, a synchronous condenser can bring other power grid stability attributes such as frequency stability by providing inertia, which is an important frequency system stability service, since it is a large rotating generator. Synchronous condensers are convenient for long transmission lines and power systems with a large amount of non-synchronous generators [25].

Secondly, the purpose of shunt capacitors is to inject reactive power into a power system with a lagging power factor [18]. A shunt reactor, on the other hand, are an inductor and absorbs reactive power when the power factor is leading, which reduces over voltages during light load conditions [17].

Thirdly, SVC is a type of shunt compensator, and is providing fast-acting reactive power. The reactors prevent the voltage to rise under low or no-load conditions by absorbing reactive power and the opposite applies for capacitors [22].

Lastly, a STATCOM consists of a voltage source converter and shunt connected transformer. The converter converts DC into AC power of variable phases angles and magnitudes [22]. A STATCOM produces reactive power by exchanging the instantaneous reactive power between the phases of the system. A capacitance is needed in the device in order to provide a circulating current path as well as a voltage source [18]. Additionally, STATCOMs can provide frequency stability by inertia [26].

2.3 Wind power plants

2.3.1 Wind energy conversion

A wind generating module overall consists of a turbine, generator, power converter and step-up transformer. To produce electricity, the turbine captures kinetic energy from the wind and allows mechanical energy to enter the generator, which in turn generates electrical energy [27]. Equation (4) explains the mechanical power output.

$$P = \frac{1}{2} C_p \rho A v^3 \tag{4}$$

Where C_p represents the power coefficient, ρ the air density, A the area of the swept blades and v the wind speed. In turn, the electrical energy generated can be calculated as equation (4) multiplied with the efficiency factor ŋ of the generator [27].

Further, the power converter is responsible for connecting the turbine with the power grid, acting as a terminal which balance the need from the grid with the turbine behavior. The step-up transformer is then transforming the voltage to a higher level, in order to access the internal collector system, before connecting to the power grid [28].

2.3.2 Full-scale converter

Type 4 electrical system for wind turbines (WTs) is a popular WT technology nowadays [29]. Type 4, shown in Figure 5, includes Full-Scale Power Electronic Converter (FSC) and can be described as a full-rated AC/DC/AC converter. The FSC itself consists of the machine-side converter (MSC), DC-link and grid-side converter (GSC) [28].

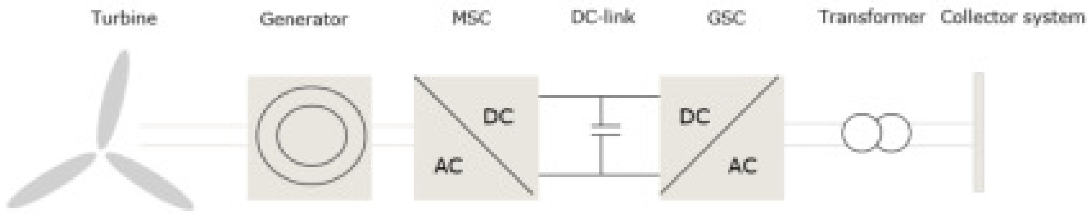

Figure 5. Simple illustration over a Type 4 WT.

In a FSC based WT, all power generated from the generator can access the power grid which leads to a high power density. The MSC controls the active power by controlling the rotational speed, while the GSC controls the active and reactive power relation and balance, which makes the FSC capable of providing important system services at grid faults or system disturbances [30]. The amount of reactive power that can be delivered by a FSC is high and it is comparable with the capabilities of a STATCOM. The reason is that the converter can handle a wide range of power production - it is even possible for certain FSC to deliver reactive power at no active power production. The behavior of a Type 4 WT can be compared with synchronous generators, such as hydro or nuclear power plants [31].

Nevertheless, the drawback, for instance in comparison with synchronous generators, is that due to the decouplement of the FSC, no system inertia is provided. Yet, synthetic inertia can be supplied with additional control methods of the converter [32] [33]. Another weakness is that the FSC has to be sized and dimensioned specifically for the capacity of the turbine, in order to being capable of function in the complete power range [31].

2.3.3 Reactive capability of full-scale converters

Capability curves are used for showing a generator's or converter's reactive power capability, as seen in Figure 6. The amount of reactive power that a converter can supply depends on voltage and current limitations, but also the active power generated.

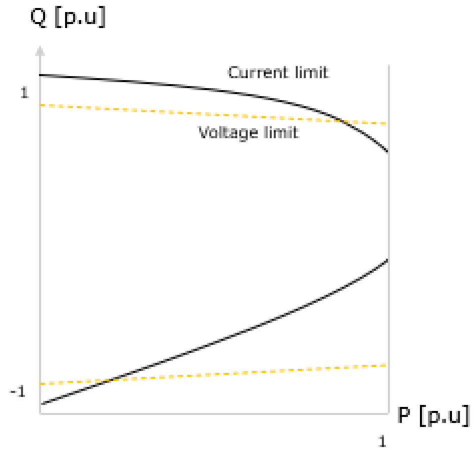

Figure 6. Theoretical reactive capability curve. The inner envelope forms the available capability.

The following expressions (equation 5, 6, 7 and 8) are retrieved from [34] via [50]. The reactive power limited by the converter voltage can be expressed as equation (5).

$$Q_V = \sqrt{(\frac{V_g V_C}{X})^2 - P^2} - (\frac{V_g}{X})^2 \tag{5}$$

Where the voltage V_g is the high-voltage side of the WT transformer, V_C the converter voltage, X is the equivalent WT inductance and P the active power generated by the WT. The upper (injection) and under (absorption) voltage limits are obtained by changing V_C to the maximum respectively the minimum allowable converter voltage. Moreover, from equation (1), the absorption and injection limits limited by the converter current can be written as equation (6).

$$Q_I = \pm \sqrt{(V_g I_C)^2 - P^2} \tag{6}$$

Where I_C is the current of the converter. Further, the two final limits that create the inner envelope showed in Figure 6, specified the maximum reactive power injection and absorption, can be derived by the following equation (7) and (8).

$$Q_{injection} = \min(Q_{I,injection}, Q_{V,injection}) \tag{7}$$

$$Q_{absorption} = \max(Q_{I,absorption}, Q_{V,absorption}) \tag{8}$$

3. Grid codes

In this chapter, European grid codes are described and compared. Grid codes are a set of technical requirements and rules for generating units to adhere to in order to be allowed connection to the power grid. It covers, for instance, system services and grid operations. The grid code applies to all system elements connected to the grid, from large scale power park modules (PPMs) on high voltage levels to single low voltage generating units [35]. More specific, grid codes of Denmark and Great Britain have been chosen to be compared with the grid codes of Sweden, due to their high installed capacity of offshore WTs [36].

3.1 ENTSO-E

The European Network of Transmission System Operators for Electricity (ENTSO-E), an alliance involving 39 European TSOs, has the mission to secure the integrated power grid in Europe and enable renewable power generation [37]. The grid codes provided by ENTSO-E are entitled as Network Codes (NC), with the aim to “facilitate the harmonization, integration and efficiency of the European electricity market” [38]. The following section is based on [39] if no other statements are made.

The NC can be divided into the Connection-, Operations- and Market Codes, where the Connection Codes refer to requirements for connecting to the physical grid. This is the codes most relevant for this research, further specific the connection code named Requirements for Generators (RfG). Other codes within Connection are HVDC (High-Voltage Direct Current) and DCC (Demand Connection Code). RfG was being implemented 2020 by national TSOs according to [40], and 21 out of 25 investigated National Regulatory Authorities confirmed that RfG had been implemented in their grid codes.

The RfG requirements vary from voltage level as well as maximum capacity of the power generating module, specified as A-, B-, C- or D modules. The A, B and C modules are expected to have a connection point below 110 kV and D modules at 110kV or above. Furthermore, RfG is adapted for different synchronous areas; Continental Europe, Great Britain (GB), the Nordic, Ireland and Northern Ireland and the Baltic. The division of modules based on capacity in the Nordic and GB are presented in Table 1.

Table 1. Module capacities for the Nordic and Great Britain.

Area	A module [kW]	B module [MW]	C module [MW]	D module [MW]
Nordic	0.8	1.5	10	30
Great Britain	0.8	1	5	75

In addition to the above categories, requirements for OPPMs, as an own category, is available in RfG. The requirements apply to networks of AC-connected power park modules located offshore with the Point of Connection (POC) offshore as well. The OPPMs can be further divided into Configuration 1 and 2:

1) “AC connection to a single onshore grid interconnection point whereby one or more OPPMs that are interconnected offshore to form an offshore AC system are connected to the onshore system;” [39]
2) “meshed AC connections whereby a number of OPPMs are interconnected offshore to form an offshore AC system and the offshore AC system is connected to the onshore system at two or more onshore grid interconnection points.” [39]

3.1.1 Voltage stability requirements and control

Reactive power capabilities at maximum active power production and below maximum active power production shall be decided by the national TSO. The requirements for reactive capability during maximum active power capacity is specified using a $U - Q/P_{max}$ – profile (Figure 8) and the reactive capability below maximum active power capacity can be explained by a $P - Q/P_{max}$ – profile (Figure 7).

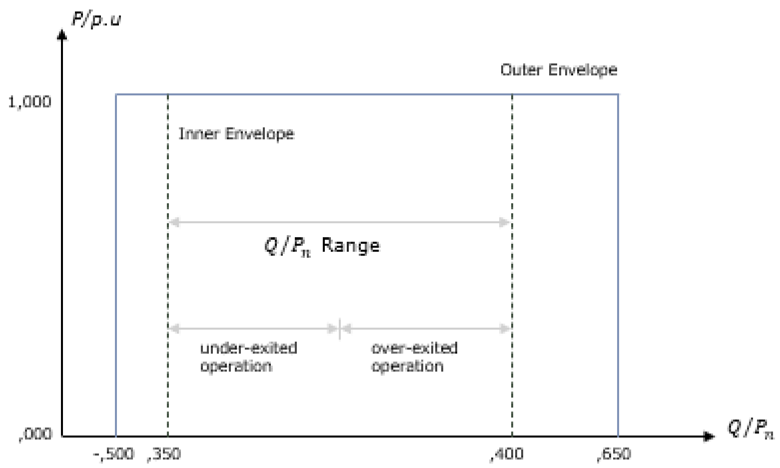

Figure 7. $P - Q/P_{max}$ – profile specified by ENTSO-E.

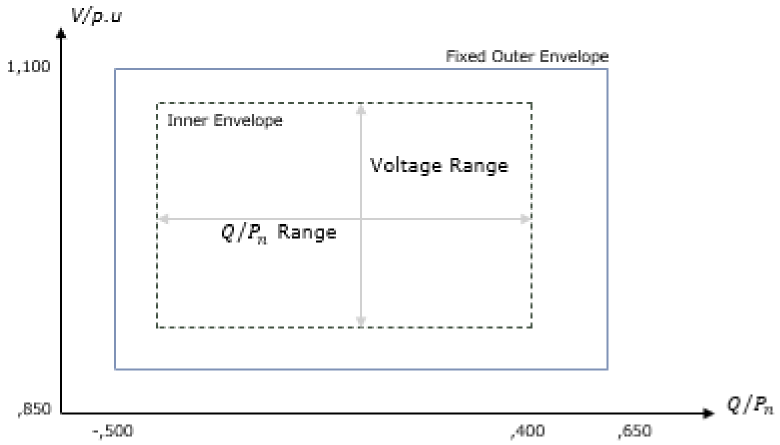

Figure 8. $U - Q/P_{max}$ *– profile specified by ENTSO-E.*

In addition, the TSO can require supplementary reactive power due to the transmission line's or cable's inductive or capacitive characteristics. Furthermore, the profile may take any form, but it is important for the specific TSO to take the potential expenses of producing or absorbing reactive power at different voltage levels into consideration when specifying the different profiles.

Moreover, the PPM must have the ability of controlling the reactive power by voltage -, reactive power - or power factor control mode:

- *Voltage control mode* means that the PPM should contribute to voltage control at the POC by changing the delivery of reactive power within a specified voltage range. Voltage control mode is visible in Figure 9.

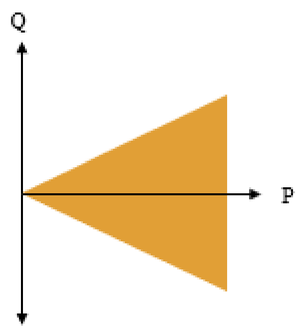

Figure 9. Voltage control mode.

- *Reactive power control mode* equals to the capability of setting the reactive power provision everyplace in the Q/P_{max} - profile. In other words, the reactive power production is not dependent on the active power generated, which is visualized in Figure 10.

Figure 10. Reactive power control mode.

- *Power factor control mode* is the method of controlling the power factor at POC. The TSO should specify the target power factor in the node whereas the grid code applies. See Figure 11 for a representation of power factor control.

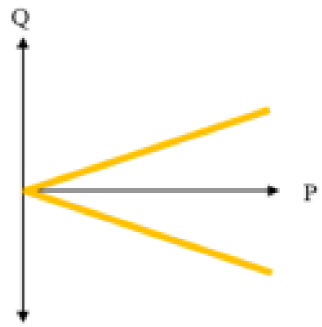

Figure 11. Power factor control mode.

The TSO together with the PPM owner should decide which of the control modes that applies and what additional equipment that is needed to meet the voltage reference in the POC.

3.2 Sweden

The Swedish interpretation of RfG is including general requirements for A-, B-, C- and D power production modules, synchronous modules, PPMs and OPPMs. The Swedish RfG is published by the Swedish regulatory authority Energimarknadsinspektionen [41].

Voltage stability requirements and control

OPPMs shall be capable of providing or absorbing reactive power exchange in the POC equivalent to one third of the instantaneous active power production. The OPPM should provide reactive power within the voltage range 90-102% and consume reactive power within the voltage range 95-105%, in the POC. In other words, this equals to retaining the reactive power $\frac{Q}{P} = \pm 0.33$ or $cos \propto = 0.95$ lead and lag in the POC. In addition, if the OPPM connects to a transmission voltage above 300kV, it shall be capable of providing reactive power compensation in the voltage range 105-110% for at least 60 minutes [41].

3.3 Great Britain

The GB Grid code is provided by the British TSO; National Grid ESO (NGESO), and is divided into several sections, for instance Connection Conditions, European Connection Conditions, Operating Code and Balancing Code. The code most relevant in this aspect is European Connection Conditions which is the updated version of Connection Conditions for generating power modules, named EU Generators, connected to the transmission system after specific dates of 2019 [42].

The code contains requirements for A, B, C and D generating modules as well as for OPPMs, but also for more specific module types, for instance HVDC Converters, HVDC Systems, Offshore Synchronous Power Generating Modules and Offshore Transmission System Development User Works (OTSDUW) [42].

Voltage stability requirements and control

The normal operating range for all power generating modules is, except for DC connected modules, 90-110% at voltage levels between 110 and 300 kV. Furthermore, different requirements are available for Configuration 1 and 2 connected OPPMs. OPPMs of Configuration 1 shall be capable of maintaining the reactive power exchange to zero in the offshore grid entry point, while Configuration 2 OPPMs, shown in Figure 12, should have the capability of providing $\frac{Q}{P_{max}} = \pm 0.165$ from 0.2 to 1 p.u. $\frac{P}{P_{max}}$, except from the range 0.2 – 0.5 at leading mode, then the requirement is changing proportionally with changing active power output [42]. This is illustrated by the dark triangle in Figure 12, which indicates that the range $\frac{Q}{P_{max}}$ = -0.165 and $\frac{Q}{P_{max}}$ = -0.12 is no requirement. Yet, both the shaded areas, dark and beige, *can* be valid with certain contracts between the TSO and module owner.

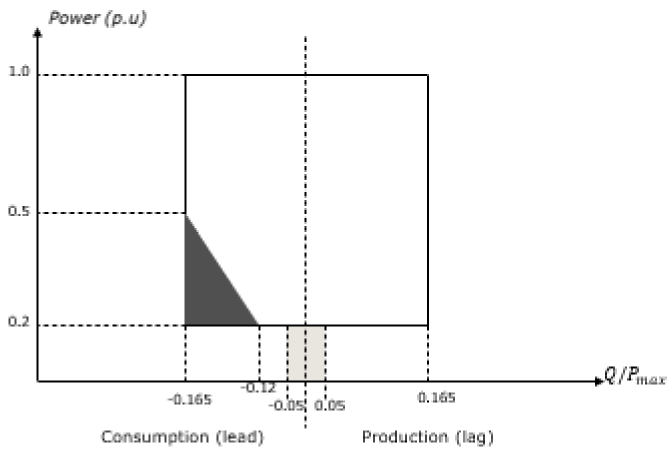

Figure 12. $P - Q/P_{max}$ *– profile for Configuration 2 OPPMs.*

In 10% voltage level range, the Configuration 2 OPMM shall be capable of function between 0.98 lead and lag at maximum capacity as shown in Figure 13.

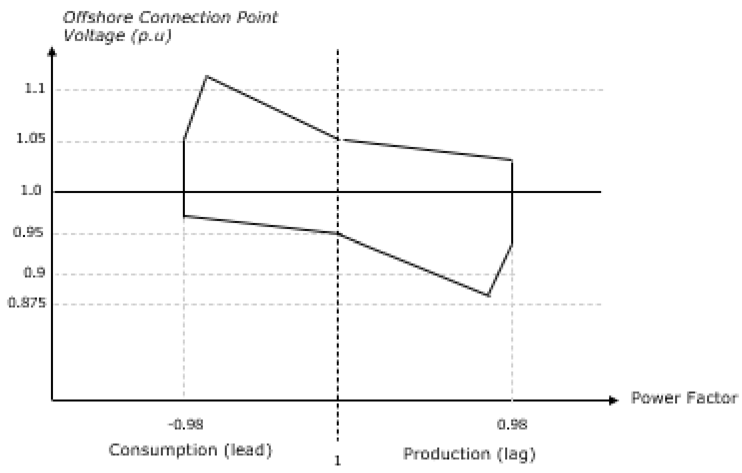

Figure 13. $U - Q/P_{max}$ *– profile for Configuration 2 OPPMs.*

Furthermore, the GB Grid code has as previously mentioned requirements for OTSDUW Plant and Apparatus, which principally means a plant which, together with the offshore transmission system, has a special agreement [43]. In such cases, the requirements must be met in the transmission systems Interface Point. In turn, the usual approach to use the maximum capacity as a measure, $\frac{P}{P_{max}}$, is no longer valid. Instead, the interface point capacity should be the reference. The interface point capacity is described as "the maximum amount of Active Power transferable at the Interface Point as declared by a User under the OTSDUW Arrangements expressed in whole MW" [42].

Figure 14 shows that OTSDUW Plants shall be capable of providing reactive power in the interface point corresponding to $\frac{Q}{P_{max}} = \pm 0.33$, and just as for Configuration 2 OPPMs, seen in Figure 12, the requirement is changing equivalently with changing active power output between 0.2 and 0.5 active power output. At maximum active power production, the $U - Q/P_{max}$ - profile is equal to the profile of Configuration 2 OPMMs, yet with the power factor 0.95 lead and lag [42].

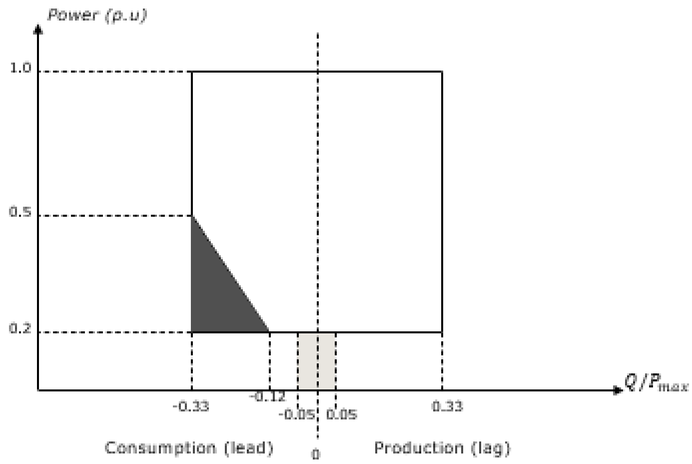

Figure 14. $P - Q/P_{max}$ *– profile for OTSDUW.*

3.4 Denmark

The Danish RfG Grid Code [44], published by the Danish TSO Energinet, contains requirements established in accordance with ENTSO-E RfG and was primary published in 2018.

Voltage stability requirements and control

PPMs and AC connected OWPPs shall have the ability to operate within $\frac{Q}{P_n} = \pm 0.33$ at the POC in the range $\frac{P}{P_n} = 0.1$ to $\frac{P}{P_n} = 1$, as shown in Figure 15. When the active power output equals to zero, no reactive power is required. From 0 to 10% of the nominal active power output, the reactive power requirements are changing proportionally with the active power.

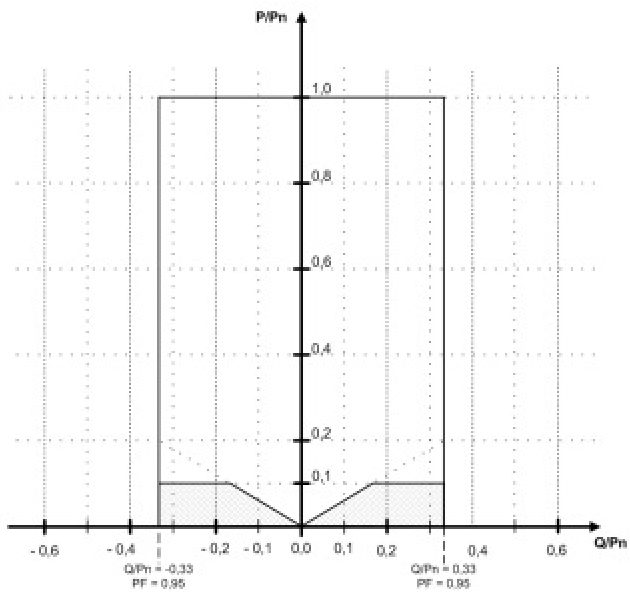

Figure 15. $P - Q/P_{max}$ *– profile for PPMs by Energinet [45].*

Figure 16 shows that at maximum active power output, the PPM, including OWPP, should be able to operate within $\frac{Q}{P_n} = \pm 0.33$, in the voltage range $U_C + 5\%$ and $U_C - 10\%$.

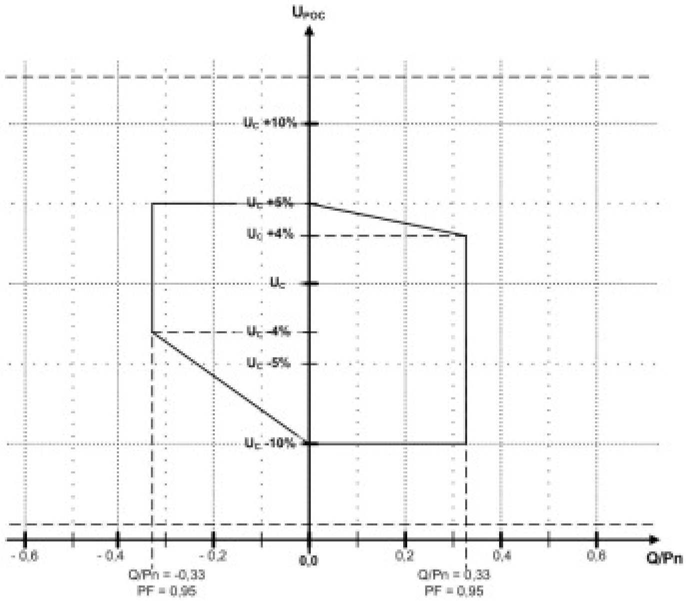

Figure 16. $U - Q/P_{max}$ *– profile for PPMs by Energinet [45].*

3.5 Comparison

To begin with, the ENTSO-E RfG should not be compared with the national grid codes since the RfG defines limits for the national TSOs to construe further and are therefore not specific requirements for power generating modules. Furthermore, it is also of importance to keep in regard that the grid code documents used in this study differ in formulation, details and content. For instance, the Swedish and Danish grid code documents are only covering RfG specifically. Nevertheless, the GB grid code is containing significantly more aspects than RfG only, for instance for HVDC connected OPPMs, as a part of the HVDC Connection Code.

Several differences and similarities are observed when comparing the different grid codes. Despite the fact that all of the grid codes are rooted in RfG, the relevant TSO for the specific country has interpreted the requirements differently. The grid code of Sweden is the one being most dissimilar in comparison with the other two grid codes, at least with regard to reactive power provision in relation to the active power generated. Firstly, no $P - Q/P_{max}$ – profile is available since the reactive power requirement is stated in relation to the instantaneous active power production instead of nominal capacity ($\frac{Q}{P_n}$) or maximum capacity ($\frac{Q}{P_{max}}$). See Figure 17 for a visualization. Secondly, neither is a $U - Q/P_{max}$ – profile available, no requirement for voltage ranges and reactive power at maximum active power output is quantified. Moreover, the GB grid code is special in that manner that no U- or $P - Q/P_{max}$ – profiles are available for a Configuration 1

OPPM. Only the requirement of a zero exchange in POC is obtainable for Configuration 1 OPPMs. Likewise, one noticeable difference between the grid codes of Denmark and GB is the way of using nominal or maximum capacity as the reference for reactive power capability.

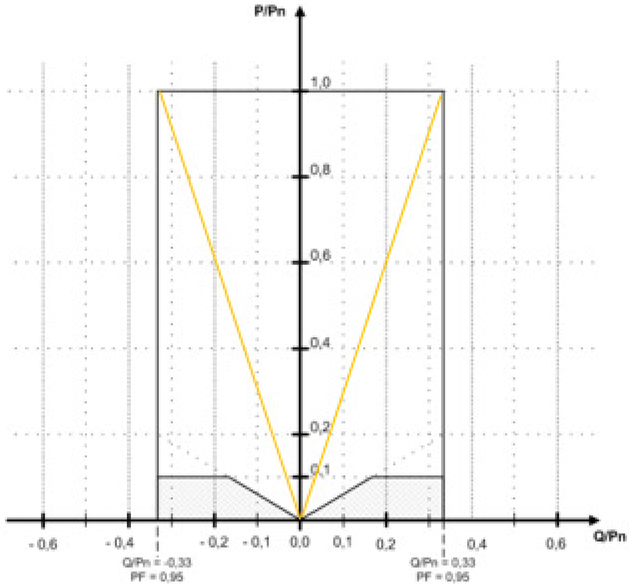

Figure 17. Swedish grid code (orange) in comparison with Danish grid code in POC.

Furthermore, the specified voltage ranges for absorption and injection of reactive power differ from the national grid codes. The grid code of Denmark requires absorption as well as injection of reactive power in the same voltage range, whereas the voltage ranges of Sweden and GB differ in the case of absorption or injection need.

Table 2. Voltage range differences between Sweden, Denmark and GB.

	Voltage range for Q consumption [%]	Voltage range for Q injection [%]
Denmark	90-105	90-105
Sweden	95-105	90-102
GB Conf. 2 OPPM	95-110	87.5/90-105

Moreover, GB is the only grid code where the requirements can be applied in another point than the connection point between the OPPM and the grid, specifically the point where the offshore grid connects to the onshore transmission grid (namely Interface Point). In such cases, the capability covers the entire offshore system behavior, not only the capability of the OPPM.

4. Case study

To investigate OWPPs capability, system behavior and compare with grid codes, a case study is performed. The model is containing a wind farm located offshore and a connected system including an offshore connection system (OCS) and a benchmark system, representing the power grid onshore. Power flow simulations are completed using the model in the software PowerWorld Simulator.

4.1 Wind farm

An OWPP with 40 WTs at 0.69 kV level is modeled. As a future scenario is considered, it is assumed that the technology has developed compared to today, yet the nominal power per turbine is assumed to be 25 MW [2]. With 40 WTs, each 25 MW, the capacity of the OWPP is 1000 MW. A majority of the assumptions made have been made with inspiration from an actual planned large-scale OWPP in Sweden [46].

The 40 turbines are connected through 10 feeders, with 4 turbines per feeder, within the internal collector network of the OWPP. One feeder is presented in Figure 18, where Line 1, 2 and 3 is assumed to be 1 km and Line 4 14 km. With the stated assumptions, the total cable length within the OWPP is 170 km.

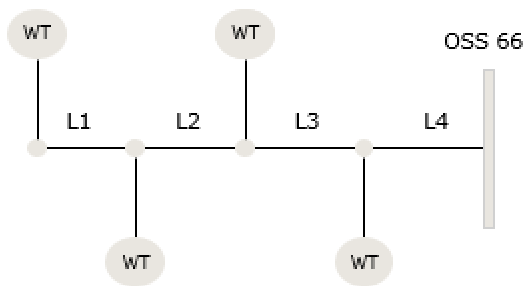

Figure 18. One feeder.

The internal collector system, shown in Figure 19, is operating at 66 kV and connects to an offshore substation (OSS 66) before being transformed up to a 220 kV voltage level.

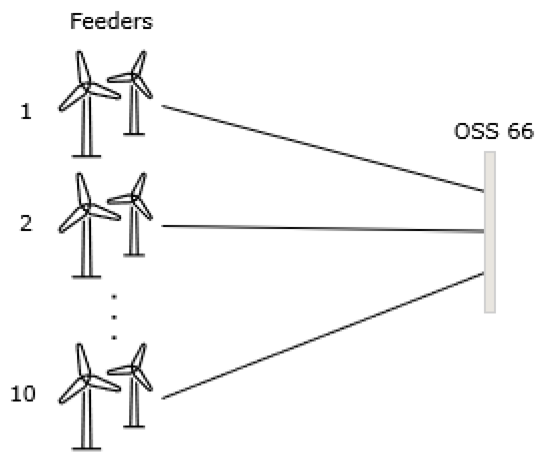

Figure 19. 10 feeders within the OWPP.

The cables used within the collector system can be seen in Table 3. Another OWPP examined uses cables with a cross-section of 630 mm^2 for 80 MW offshore wind production, whereby it is comparable to one feeder of the OWPP [47]. The same cable type is assumed for all lines within the OWPP. The parameters can be found in [48] and [49].

Table 3. Internal collector cables.

Voltage [kV]	66
Cross-section of conductor [mm^2]	630
Capacitance [µF/km]	0.32
Inductance [mH/km]	0.33
AC resistance (20°C) [Ω/km]	0.045

4.1.1 Reactive power output

A method for receiving the converter voltage and current limits, specified for one wind farm as one aggregated unit, Z_{WPP}, instead of one single converter, is used. By taking the entire impedance of the collector system within the farm into account, instead of scaling-up the converter capability to the total production of the farm, important system aspects such as losses within the wind farm are not neglected [50].

Certain modifications have been made by [50] in the converter limit expressions in Section 2.3.3 in order to adapt the expression for the entire WPP instead of one WT, shown in the following equations:

Equation (5) has been updated to:

$$Q_V = \sqrt{(\frac{V_g V_C}{|Z_{WPP}|})^2 - (P - \frac{V_g^2 R_{WPP}}{R_{WPP}^2 + X_{Wpp}^2})^2} - \frac{V_g^2 X_{WPP}}{R_{WPP}^2 + X_{Wpp}^2}$$

(9)

Equation (7) and (8) have respectively been modified to:

$$Q_{injection} = \min(Q_{I,injection}, Q_{V,injection}) + B_{coll} {V_g}^2$$

(10)

$$Q_{absorption} = \max(Q_{I,absorption}, Q_{V,absorption}) + B_{coll} {V_g}^2$$

(11)

Where B_{coll} is the total susceptance of the collector system, Z_{WPP} is the aggregated OWPP impedance and V_g the voltage at the low voltage side of the 66/220 transformer.

The equivalencing of the cables of the collector system, Z_{coll} and B_{coll}, is made using the method from [51], based on circuit analysis, and the parameters from Table 3. Further, by adding Z_{coll} and $Z_{WT,}$ the final aggregated impedance of the entire OWPP, Z_{WPP}, is obtained and presented in Figure 20.

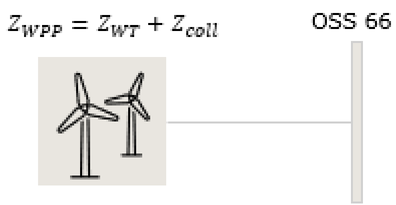

Figure 20. Representation of OWPP aggregated impedance.

The converter's voltage and current design, $V_{C,MAX}$, $V_{C,MIN}$ and $I_{C,MAX}$, is assumed to be the same as in [50], as there is limited information about converter designs available. The impedance of one single WT is assumed to be $Z_{WT} = 0.022 + j0.156\ p.u.$, including the cable stated in Table 3 as well as 0.69/66 kV transformer and filter [52]. Worth mentioning is the fact that the dimensioning of the converter is of importance for the resulting capability, as shown in [34]. Moreover, by using the parameters in Table 4 and the equations (6), (9), (10) and (11), the reactive capability curve in Figure 21 can be presented for the 1000 MW OWPP.

Table 4. *Parameters for reactive power capability plotting in p.u.*

$I_{C,MAX}$	1.25
$V_{C,MAX}$	1.1
$V_{C,MIN}$	0.8
Z_{WT}	$0.022 + j0.156$
Z_{coll}	$0.015 + j0.035$
B_{coll}	0.062

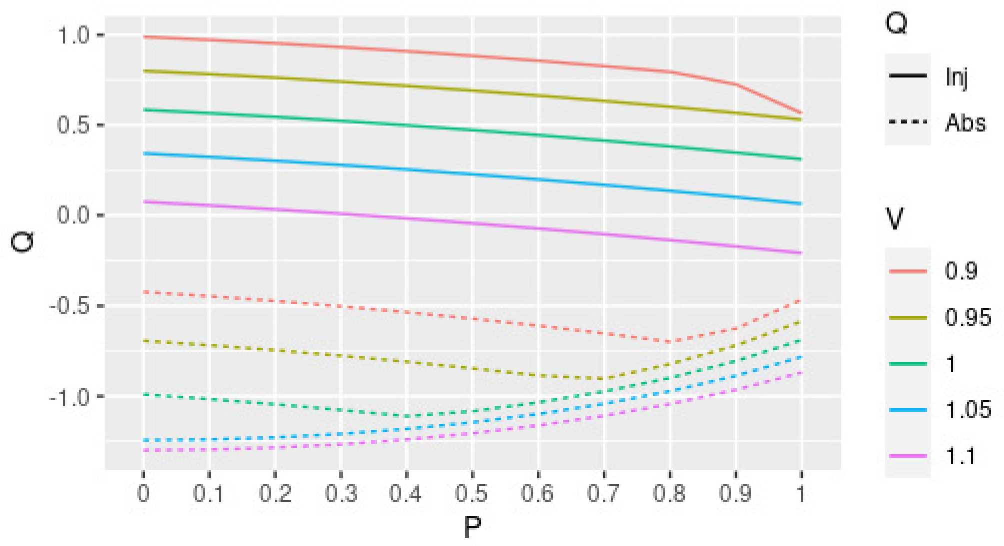

Figure 21. Reactive power capability at POC for presented OWPP. See Appendix A for the R-Studio code used for plotting.

4.1.2 Converter sensitivity analysis

As stated, the dimensioning of the converter has an impact of the resulting capability [34]. In this section, the influence of the converter design is evaluated for the OWPP. Table 5 shows the impact of the current dimension and Table 6 the impact of the voltage dimension. The analysis is made at 1 p.u. voltage, $\frac{P}{P_n} = 0.5$ and the percentage values in the tables are representing the deviations from the chosen converter design at row one.

Table 5. Different converter current dimensions and capability impact.

$I_{C,MAX}[p.u.]$	$Q_{MAX}[MVar]$	$Q_{MIN}[MVar]$	$\%_{Q,max}$	$\%_{Q,min}$
1.25	472	-1083	-	-
1.20	472	-1029	-	5
1.15	472	-974	-	10
1.1	472	-918	-	15

Table 6. Different converter voltage dimensions and capability impact.

$V_{C,MAX}[p.u.]$	$Q_{MAX}[MVar]$	$Q_{MIN}[MVar]$	$\%_{Q,max}$	$\%_{Q,min}$
1.1	472	-1083	-	-
1.05	206	-1083	-56	-
1	-62	-1083	-113	-
0.95	-331	-1083	-170	-

As one can perceive from Table 5 and Table 6, the converter is considerably more sensitive to changes in the dimensioning of the voltage perimeter in comparison with the current tolerance. Changing the current in steps of 0.05 p.u., the maximum absorbing amount of reactive power increases with 5 %. Decreasing the converter voltage, the maximum reactive power that can be injected decreases significantly – a first decrease with 56% in capability when changing the maximum acceptable voltage with -0.05 and in total a decrement of -170%, changing the voltage with 14% (from 1.1 to 0.95 p.u.).

4.2 Connected system description

4.2.1 Benchmark model

In order to investigate OWPP's reactive power capabilities on the onshore power grid, a benchmark model is used. The model is retrieved from Svk and is designed for static studies of voltage regulation. Moreover, the model represents a fictive grid, and the purpose is to replace the synchronous generator with an OWPP. The benchmark model is presented in Figure 22. The synchronous generator is capable of generating 1000 MW and is located at the 'GENBUS'. Furthermore, the Point of Interconnection (POI) is the connecting point onshore and is where the OCS to the OWPP will be attached. The 'GRIDBUS' is the nearest meshed point to the transmission grid and is also the location of a load and one shunt. The load is initially generating at 4000 MW and the shunt at 0 MVAr.

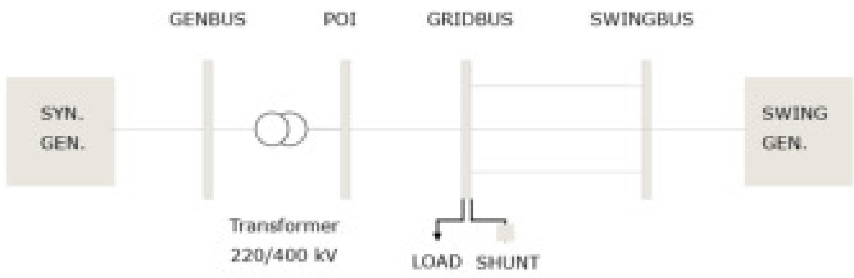

Figure 22. Benchmark model for static studies of voltage regulation.

4.2.2 Offshore connection system

The OCS from the OWPP to POI is shown in Figure 23. The system consists of an offshore substation (OSS), an onshore substation (OnSS), and two HVAC export cables connected between these substations. The HVAC export cables are 20 km long as that is the approximated distance from the coast, still within Sweden's territorial waters [46], where Svk potentially will expand the transmission grid. More precisely, the OSS consists of two 66/220 kV transformers which connects to two HVAC cables. There are two cables due to the large amount of power being transported from the OWPP and because a two-parallel-cable solution increases the reliability. A design with two cables instead of one could have an impact on the amount of reactive power being produced in the OCS. The HVAC cable is connected to an OnSS, which is equipped with one 220/400 kV transformer. The construction in Figure 23 is inspired by the AC OCSs from a large-scale OWPP to the main grid in [53] and [54]. Both [53] and [54] is designing the OSS with two transformers and the OnSS with one transformer, as that is a typical configuration of this type of system. The configuration in Figure 23 is additionally based on parts from an overview of a non-public principal concept of an OCS for 1000-1200 MW OWPP received from Svk. OSS 220 in Figure 23 is the POC, and from that point Svk is expected to own the offshore transmission grid.

Figure 23. Schematics of the OCS from the OWPP to the POI.

Offshore transmission systems can be equipped with a reactive compensation station (RCS), to compensate for reactive power generated in the cables. The OCS in this case study is not equipped with an RCS as the purpose of the simulations is to investigate the OWPP capability to ensure onshore grid stability.

Transformers

As has been stated, the OSS consists of two transformers and the OnSS of one. The input data of the transformers are scaled up to match the OWPP in this case study. The OSS transformers input data is based on a 350 MVA 66/220 kV transformer and scaled up to 500 MVA. Further, input data of the OnSS transformer is based on a 620 MVA 220/400 kV transformer and scaled up to 1000 MVA. The general losses in a transformer are mainly load and no-load losses, which can be determined through short-circuit test and open-circuit test. The equivalent series resistance (R_{eq}) and reactance (X_{eq}) in a transformer are the sending and receiving side reactance/resistance combined, which are determined in a short-circuit test and causes load losses [55].

The resistance of the excitation branch and the mutual magnetic flux represents the transformers core. These are determined in an open-circuit test and causes no-load losses [55]. The core is neglected in the transformers in the OCS, as the differences with and without a core is small. The transformers absorb overall around 1% less reactive power without a core in comparison to with a core included. The model is therefore simplified as it has a small effect on the simulation results. Input data for the two transformers in the OCS is presented in Table 7 and selected based on [53].

Table 7. Transformers in OCS.

	OSS Transformers	OnSS Transformers
S_{Nom} [MVA]	500	1000
Ratio (α) [kV]	66/220	220/400
R_{eq} [p.u.]	0.0035	0.00192
X_{eq} [p.u.]	0.112	0.1024

HVAC Export Cables

HVAC export cables in this case study is three-core cables with cross linked polyethylene (XLPE). This type of HVAC export cable is dominantly for wind farms [56]. According to [49] the submarine cable is laying a temperature of 20°C in seabed. As mentioned in 2.1.3, important aspects within cable design are the required current carrying capacity and the corresponding cross-section of the conductor. A similar OWPP as the farm in this case study is modeled in [53] and is using a cable with a cross-section of 800 mm^2. The current carrying capacity has been estimated for this case study by calculating the reactive power consumption and thereby the current flow in the two transmission cables. This resulted in a required capacity of 734 A and therefore a cable design with a cross-section of 800 mm^2 and 775 A rated current is chosen. The data for the cable is presented in Table 8 and is selected based on [53] and [49].

Table 8. HVAC Export Cable.

Type	XLPE Submarine Cable Three-core cable with lead sheath
Voltage [kV]	220
Cross-section of conductor $[mm^2]$	800
Current carrying capacity [A]	775
Capacitance [μF/km]	0.17
Inductance [mH/km]	0.4
AC resistance (20°C) [Ω/km]	0.0246

Verification of the offshore connection system

In order to verify the OCS from the OWPP to the POI, the power flows in the system have been calculated in MATLAB and compared with the simulated values in PowerWorld Simulator. The receiving side voltage, active - and reactive power was used as input values to first calculate the receiving side current and further used in equation (3). By multiplying receiving side voltage and current with the ABCD parameters the results show the sending side current and voltage. The active - and reactive power on the sending side could thereby be calculated using the sending side voltage and current. When comparing calculated values with simulated, the differences overall are less than 1%, which is considered good. For further information see the MATLAB code and the verification tables in Appendix B.

4.2.3 Final representation of model

When combining the previous presented system parts (OWPP, OCS and benchmark model), the final representation of the test system is obtained and showed in Figure 24. A representation of the system established in PowerWorld Simulator can be found in Appendix C.

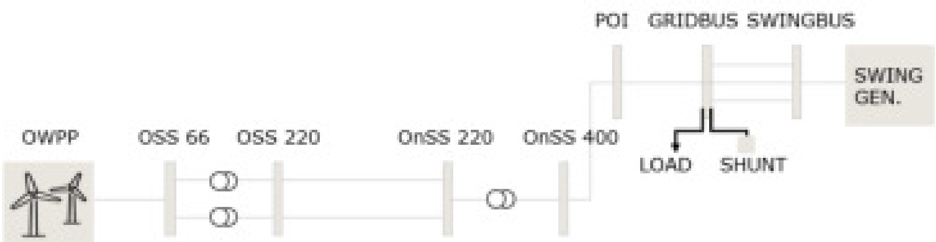

Figure 24. Final test system with OWPP, OCS and benchmark model.

4.3 Simulations

In this part, power flow simulations are introduced for the final model in Figure 24, in order to evaluate the inductive and capacitive capability of the OWPP to provide voltage stability onshore. It is of importance to be aware of that the aim of the simulations is to investigate system performance and capability, not necessarily making the system as stable as possible. Moreover, the power flow simulations are of static characteristics, which means that the power flows during steady-state and is a function of voltage [57]. Steady-state stability can be defined as “the ability of a power system to remain stable” [58].

4.3.1 Methodology

In order to test the OWPPs capability and ability to reach grid codes, the benchmark system properties were changed by changing the load and available transmission lines to create a need for injection or absorption of reactive power. Table 9 is a description over the final system’s base case. The active and reactive power generated by the OWPP are set to zero in the base case in order to receive a system reference.

Table 9. Base case.

$P\ load\ [MW]$	4000
$Q\ load\ [MVAr]$	0
$Shunt\ [MVAr]$	0
$V_{OSS220}\ [p.u.]$	1.01
$V_{POI}\ [p.u.]$	0.99
$V_{GRID}\ [p.u.]$	0.98
$Q_{POI}\ [MVar]$	133

The base case of the final test model is considered as stable, since no remarkable deviation in voltage is visible; 99 % of voltage reference in POI as seen in Table 9. Therefore, two main scenarios, A and B, were established, corresponding to the TSO or power grid demanding/needing leading or lagging reactive power, respectively:

Scenario A) Over-voltage
Scenario B) Under-voltage

Moreover, for each of the scenarios, two sub-scenarios were formed in order to test different levels of inductive and capacitive needs from the grid. The sub-scenarios A1, A2, B1 and B2 represent different voltage deviations from the base case in the system, shown in Table 9. The individual scenario attribute can be observed in Table 10 and identical to the base case, the OWPP load is set to zero.

Table 10. Scenario attributes.

	A1	A2	B1	B2
System status	Over-voltage	Over-voltage	Under-voltage	Under-voltage
P load [MW]	2000	0	6000	8000
Q load [MVAr]	0	-500	0	0
Shunt [MVAr]	0	0	0	0
V_{OSS220} $[p.u.]$	1.04	1.1	0.96	0.85
V_{POI} $[p.u.]$	1.02	1.07	0.94	0.83
V_{GRID} $[p.u.]$	1	1.06	0.93	0.82
Available transmission lines between 'Gridbus' and 'Swingbus'	3	2	3	3

The initial load in the benchmark model is as previously mentioned set to 4000 MW, of which changes with steps of 2000 MW for each scenario were made in order to create an under- or over-voltage deviation with the base case as reference.

Furthermore, for each of the scenarios, based on active power production from the OWPP in relation to the nominal production, $\frac{P}{P_n}$, different reactive power outputs were tested based on grid code requirement and technical capability.

Table 11. OWPP production and Swedish grid code requirements.

P [MW]	$\frac{P}{P_n}$	$Q_{req.,abs.}$[MVAr]	$Q_{req.,inj.}$[MVAr]
0	0	0	0
200	0.2	-66	66
500	0.5	-165	165
800	0.8	-264	264
1000	1.0	-330	330

Firstly, the maximal Swedish grid code requirement in POC was tested for the specific active power output, as shown in Table 11. POC is the point where Svk is expected to own the offshore transmission grid, and to clarify, POC is called OSS220 in Figure 23. Secondly, the theoretically reactive capability was tested for the specific active power output, with regard to the capability curve in Figure 21. Thirdly, the grid code requirement was fulfilled by a shunt onshore. The MVAr load of the shunt was modified until reaching the same V_{POI} as in the capability testing, when the OWPP fulfilled the grid code requirement. In this way, the amount of reactive power from the shunt and the amount of reactive power from the OWPP could be compared. In order to visualize the methodology behind the simulations, a schematic diagram is used. Using the presented methodology in Figure 25, a total amount of 66 simulations were made.

For each OWPP output $\frac{P}{P_n}$ for scenario A1, A2, B1 and B2, the methodology scheme in Figure 25 was demonstrated.

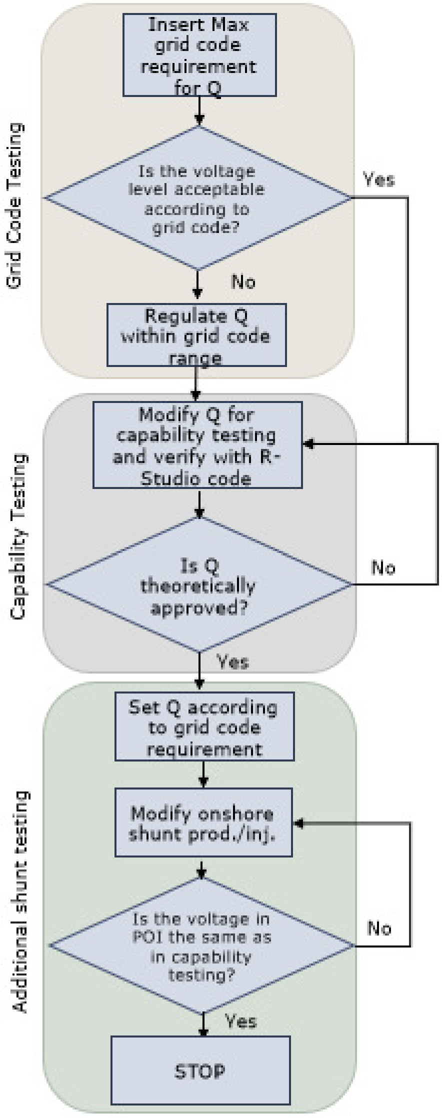

Figure 25. Methodology scheme for grid code-, capability- and additional shunt testing.

Finally, 20 simulations descend from simulations other than the above presented. Simulations were made in order to test grid code in POI instead of POC, in other words the grid codes of GB. The reactive power output from the OWPP was changed in order to fulfill the reactive power exchange requirement in POI.

Hence, the following four cases were tested for the scenarios A1, A2, B1 and B2:

- *Grid code in POC (Swedish)*
- *Theoretical reactive power capability*
- *Additional shunt compensation*
- *Grid code in POI (GB)*

4.4 Simulation results and analysis

Through the methodology in Section 4.3.1, simulations on the final test system in Figure 24 were completed. All of the simulation results were established in Microsoft Excel in order to be analyzed and compared. In this section, key simulation results are shown. Moreover, the results presented in this section are from the scenarios A1, A2, B1 and B2, for the four stated cases above. All scenarios were tested in the simulations, yet only one of the over/under-voltage scenarios is presented under each italicized heading as the results are similar. Thus, all of the simulation results can be found in Appendix D.

4.4.1 Grid codes

Distance impact
Figure 26 and Figure 27 show the impact of the distance between the OWPP and POI on reactive power transfer. Both Figure 26 and Figure 27 are simulated on the final test system, which means that the distance is equal for both scenarios yet depending on the active power production from the OWPP the losses in the OSC is different. Furthermore, Figure 26 and Figure 27 are showing the results when simulated the case Grid code in POC (Swedish). Figure 26 is the results of the under-voltage scenario B2 and Figure 27 the results of the over-voltage scenario A2.

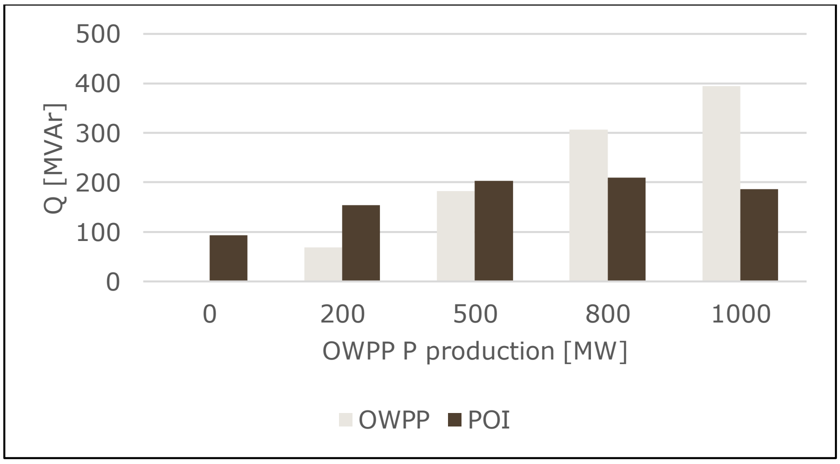

Figure 26. OWPP reactive power production and the amount of reactive power at POI when simulating grid codes in POC. Results of scenario B2.

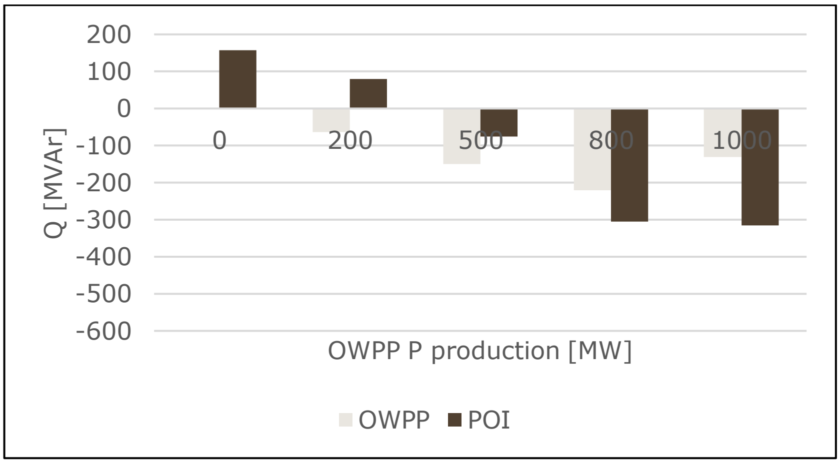

Figure 27. OWPP reactive power production and the amount of reactive power at POI when simulating grid codes in POC. Results of scenario A2.

If the production of active power increases, the amount of current flowing through the system increases. The increased current through the impedances results in an increased amount of reactive power being absorbed in the inductive elements and the OCS becoming inductive. This is the case in Figure 26 and Figure 27 when the active power production is around 500 MW. In the range 0-500 MW in Figure 26, the amount of reactive power at POI is larger than the OWPP produces due to the capacitive behavior in OSC. At 800-1000 MW the OCS is inductive and the OWPP produces more reactive power than the amount reaching POI. However, when the active power is 1000 MW in Figure 27, there is no need to absorb reactive power as the OCS is inductive, which results in less absorption from the OWPP. In the same figure, when the active power is 200 MW, the OWPP absorbs reactive power, yet the reactive power reaching POI is leading as the OCS is capacitive. To summarize, during low active power production, the OCS has a capacitive behavior and at high production the behavior is inductive.

Grid code at POC versus POI

The Swedish grid code applies in POC, while in GB they can apply in POI in the case of a OTSDUW contract. Figure 28 are showing the impact of the different types of grid codes for the under-voltage scenario B2 and over-voltage scenario A2.

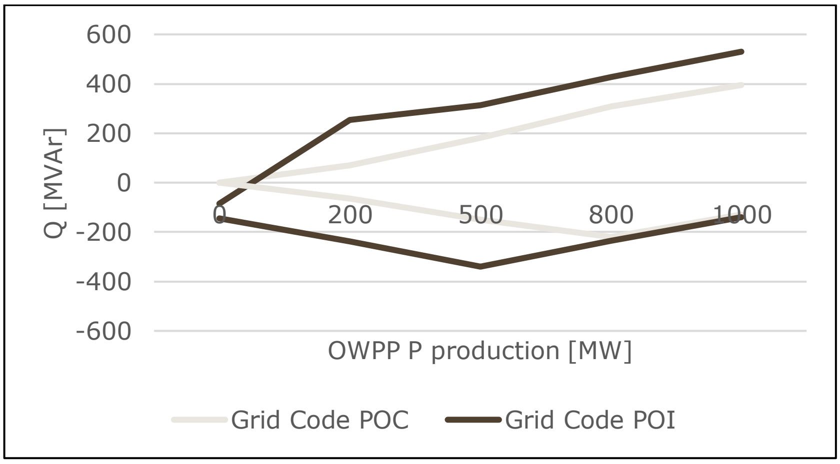

Figure 28. OWPP reactive power production when simulating grid codes in POC and grid codes in POI. Results of scenario A2 and B2.

As the voltage stability control requirements in GB grid codes is higher than in Sweden, as well as applies in another connection point, more leading and lagging reactive power production is required in order to reach the requirement at POI in GB grid codes. The changed behavior of the OCS, from capacitive to inductive, is visible in Figure 28 between 500 – 800 MW. At 0 MW, the OWPP has to absorb reactive power in order to achieve a zero-exchange at POI. Furthermore, as the need of lagging reactive power is less during high active power production, the difference of reactive power production when simulating grid code in POC versus POI is close to zero. However, the main difference between the two grid codes is during low active power production. Furthermore, Figure 29 and Figure 30 shows how the amount of reactive power is affecting the voltage level when simulating the grid codes in POC (Swedish) and in POI (GB). Figure 29 is representing the under-voltage scenario B1 and Figure 30 the over-voltage scenario A1.

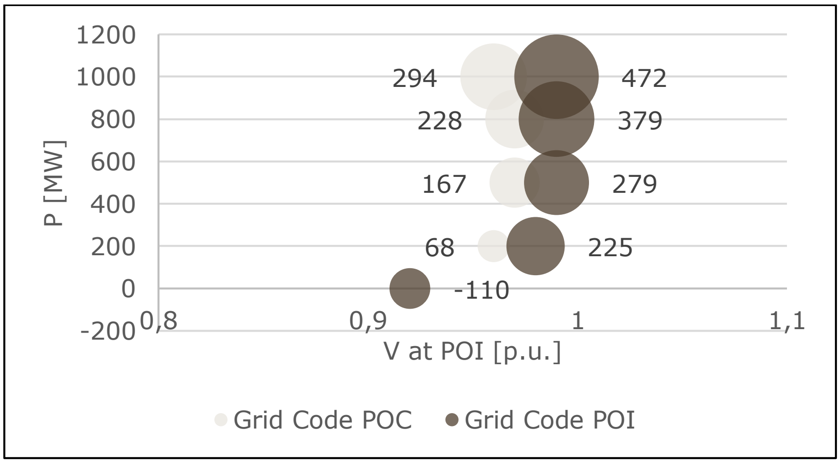

Figure 29. OWPP reactive power production and the corresponding voltage level in POI when simulating grid code in POC (Swedish) and grid code in POI (GB). Results of scenario B1.

Figure 29 is showing that the higher the OWPP reactive power production is, the higher the voltage in POI. As the GB grid codes require a wider reactive power production range, the voltage levels become naturally higher. In scenario B1 the voltage is nearly between 0.9 p.u. and 1 p.u. for all the points, which means the required voltage level interval is achieved when simulating the two different grid codes.

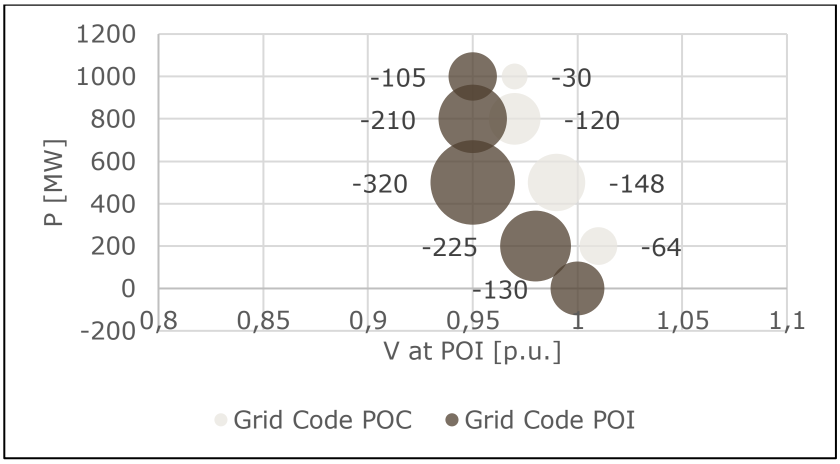

Figure 30. OWPP reactive power production and the corresponding voltage level in POI when simulating grid code in POC (Swedish) and grid code in POI (GB). Results of scenario A1.

For the over-voltage scenario A1 presented in Figure 30, the GB grid code results in an increased absorption of reactive power compared to the Swedish grid codes. This results in a lower voltage level. However, all the points in Figure 30 are within required voltage level interval.

4.4.2 Reactive capability

Reliability and distance impact
As previously determined, the distance from the OWPP and onshore grid affects the amount of reactive power reaching POI. Figure 31 and Figure 32 is showing the difference between the OWPP reactive power capability and the reactive power in POI. Figure 31 is showing the results from the under-voltage scenario B2 as well as the over-voltage scenario A2. Figure 32, on the other hand, is showing the results from B1 and A1.

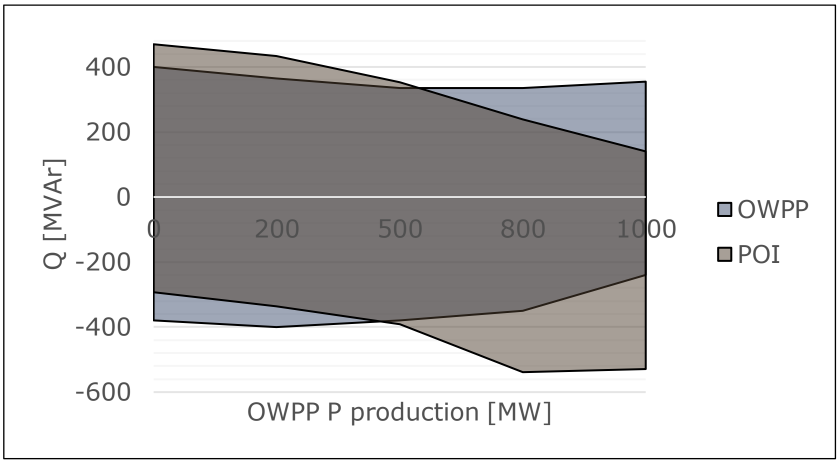

Figure 31. OWPP reactive power production and the amount of reactive power at POI when simulating the capability. Results of scenario A2 and B2.

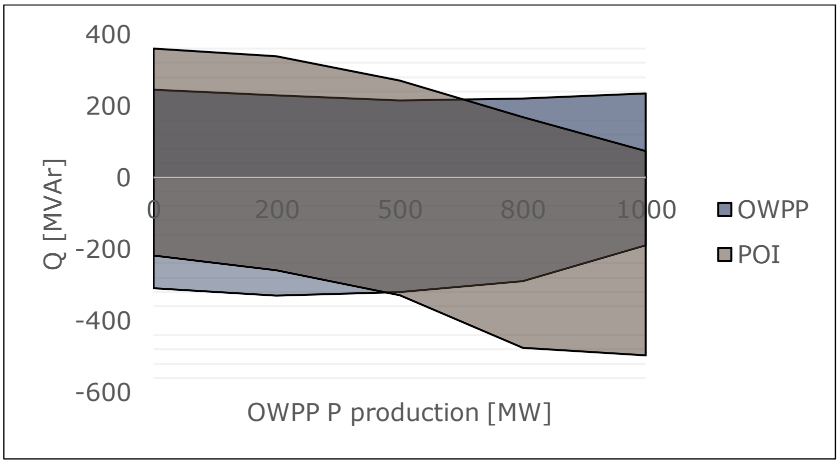

Figure 32. OWPP reactive power production and the amount of reactive power at POI when simulating the capability. Results of scenario A1 and B1.

In the range 0 – 500 MW the reactive power at POI is more leading than what the OWPP produces as the OCS is capacitive. The opposite applies between 500 – 1000 MW as the OCS is inductive. Furthermore, the OWPP's reactive power output is reliable in the range 0-1000 MW for both the under- and over-voltage scenarios in Figure 31 and Figure 32. During over-voltage, the output is more affected by the behavior of the OCS as the need of lagging reactive power is less. In addition, the OWPP capabilities of absorbing reactive power is greater than producing during low active power production.

OWPP capability versus shunt compensation

In Figure 33 and Figure 34 the reactive power capability of the OWPP is compared with a shunt placed onshore, with regard to the ability to obtain the same voltage level in POI. The reactive power is measured in the POI in order to make a reasonable comparison. Figure 33 is representing the under-voltage scenario B1 and Figure 34 the over-voltage scenario A1.

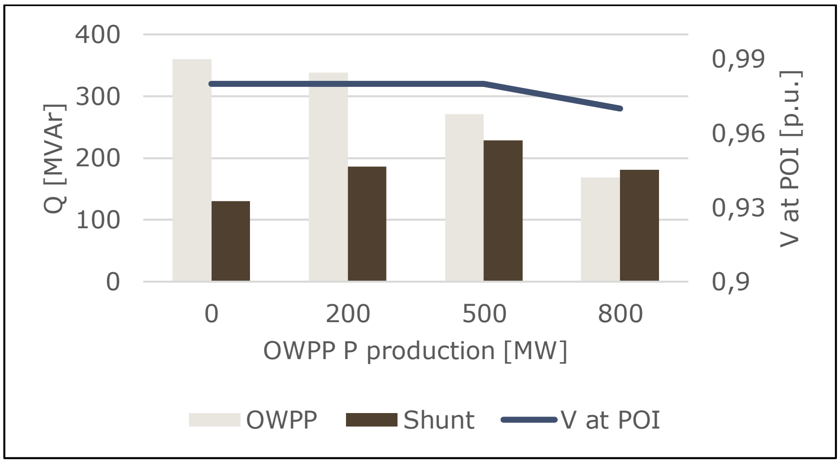

Figure 33. OWPP capability at POI versus shunt production at POI, reaching the same voltage level. Results of scenario B1.

The amount of reactive power from the shunt reaching POI is considerably lower in comparison to the reactive power produces by the OWPP at zero active power production. When increasing the OWPPs active power production and corresponding maximum reactive power, the shunt has to increase MVAr production as well in order to obtain the same voltage. When reaching OWPP production of 800 MW, the shunt has a higher amount of reactive power at POI.

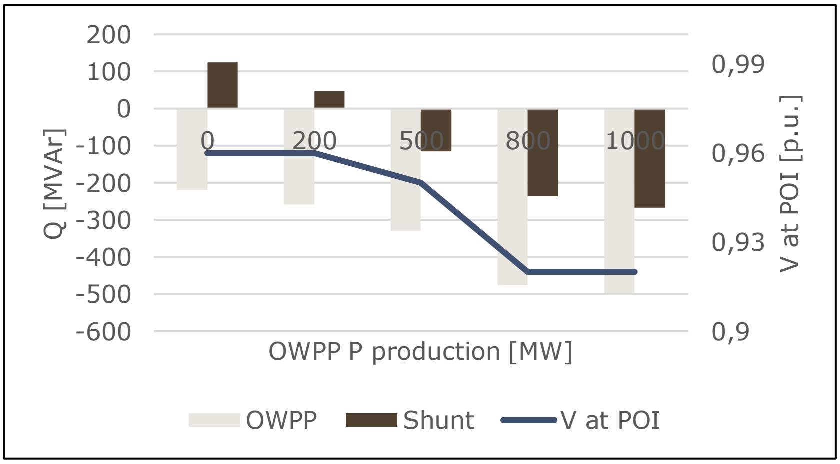

Figure 34. OWPP capability at POI versus shunt production at POI reaching the same voltage level. Results of scenario A1.

Comparing Figure 34 with Figure 33, one can notice the more volatile behavior of the shunt, changing from leading to lagging due to the capacitive appearance of the OCS. In the range 0-1000 MW, the shunt is absorbing less reactive power in the POI than the amount of lagging reactive power at POI by the OWPP.

4.4.3 Grid code and reactive capability comparisons

The OWPPs reactive power capability is compared to the reactive power production to fulfill the grid code in POC (Swedish) for under- and over-voltage. Figure 35 is showing the scenario B2, which is under-voltage, and Figure 36 is showing the scenario A2, which is over-voltage.

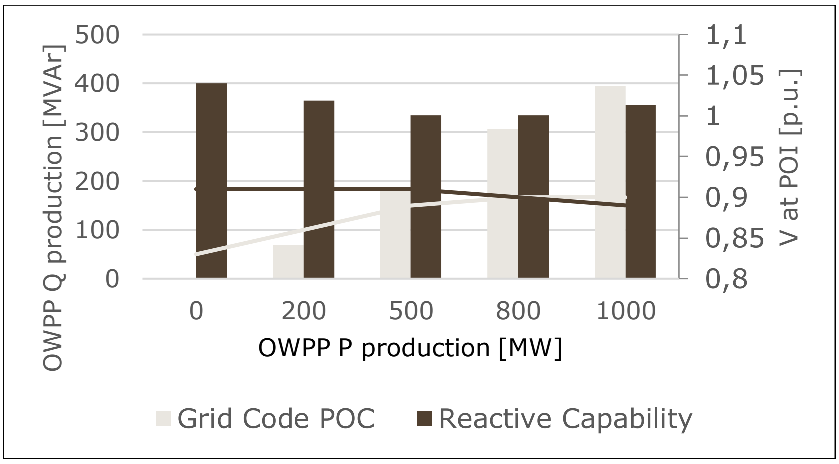

Figure 35. The bars represent OWPP reactive power production and the lines the voltage level at POI. Results of scenario B2.

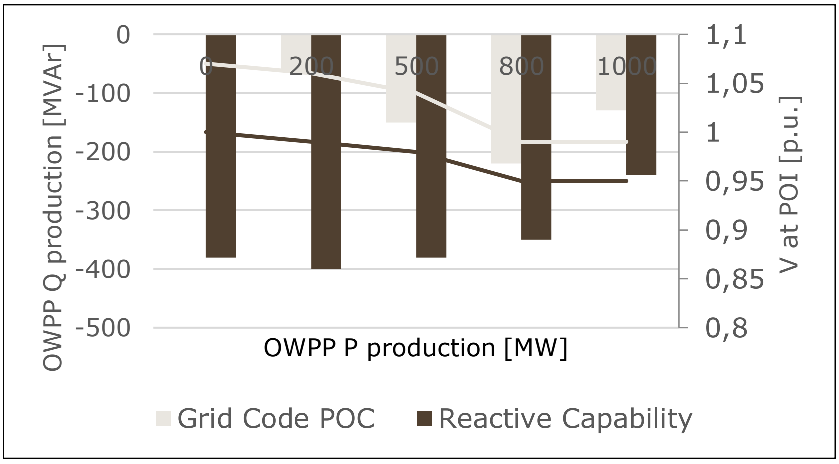

Figure 36. The bars represent OWPP reactive power production and the lines the voltage level at POI. Results of scenario A2.

Figure 35 and Figure 36 is showing that OWPPs capability is significantly higher than grid code requirements. As a larger amount of reactive power leads/lags, the voltage increases/decreases when simulating the capability in comparison to grid code. In the under-voltage scenario, Figure 35, the OWPP has greater capability to increase the voltage during low active power production and in the over-voltage scenario, Figure 36, the capability to decrease the voltage is the highest during high active power production. The behavior is affected by the OCS capacitance/inductance behavior as mentioned before.

5. Market for reactive power

In the following chapter a reactive power market opportunity analysis is presented and discussed. Firstly, Section 5.1 covers the foundations of the design of a reactive power market. Moreover, Section 5.2 and 5.3 consist of a discussion where the information in 5.1 is applied on the simulated OWPP that was presented in Chapter 4.

5.1 Design of a reactive power market

There are different important aspects to consider when designing a reactive power market. For instance, voltage security and cost efficiency [59]. A market design can affect whether there are enough reactive power resources to secure voltage stability. Moreover, the degree of cost efficiency for the TSO and the reactive power provider can vary depending on the design. The degree of market-based or regulated approach can differ in a market design. Figure 37 ranging market designs from strictly regulated to purely market-based approaches. In the left end of Figure 37, the approach is regulated with grid code requirements and to the right the approach is market-based with ongoing procurement [15].

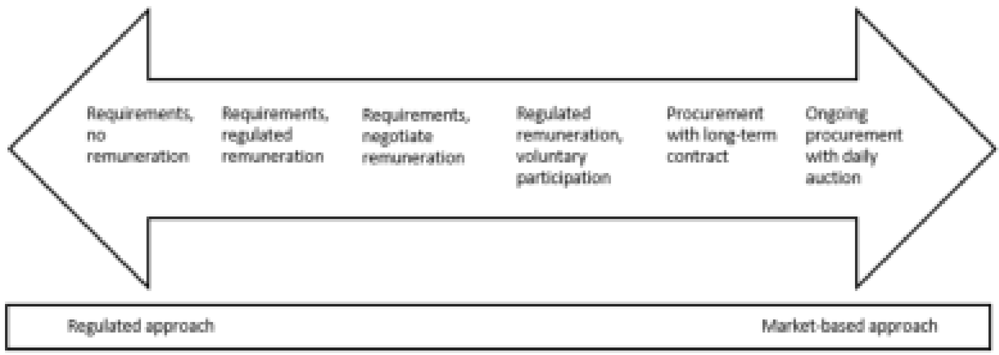

Figure 37. Different market approaches.

With a regulated approach through strict grid code requirements, the TSO can have high security regarding the installed capacity but receives limited information about the provider's costs for delivering the service. There could therefore be a risk that the grid code requirements are too cost-driving for providers and society. This is especially the case when the cost for delivering the service differs between providers. In these cases, a market-based approach can be more cost-effective, as the provider with the lowest costs can provide its capabilities. Additionally, since it is the providers choice whether they want to be connected and in operation, there is a risk regarding missing availability for the TSO and therefore the TSO could end up in a position of dependency of the provider. Moreover, grid code requirements are usually designed according to existing providers and not new ones, which means that a regulated approach could primarily benefit the existing providers. In contrast, a completely market-based approach is not based on grid code requirements and can therefore provide incentives for both new provider and existing ones. With a market-based approach, the TSO can be given more information about the provider´s costs of reactive power at a given volume and quality, which can enable more efficient activation of resources in the operational phase [15]. As the aim of the thesis is to investigate how a reactive power market can be designed, the main focus in this chapter is on a market-based approach and not on a regulated approach.

5.1.1 The localized nature of reactive power

Reactive power cannot be transmitted over long distance, as it has a localized nature [60]. This behavior affects providers effectiveness of providing reactive power to a specific node. The effectiveness depends on physical factors, for instance the plants proximity of the electrical grid. In order to allow fair assessment of all potential providers at different locations, the effectiveness should be considered in the market design [59]. An electricity market could be designed with nodal or zonal pricing. With nodal pricing each producer is paid in accordance with the local price of the location of the node. In zonal pricing, nodes are collected into zones and the price inside a zone is the same [61]. [16] means that nodal pricing for reactive power could be the most beneficial in order to secure the system stability because of the technical realities with reactive power. Meanwhile [62] propose a zonal reactive power market as the impact of market power is minimized when the price is restricted within a zone only. The zones are, in [62], divided into different voltage zones based on the concept of electrical distance and every zone is acting as a separate market.

A market-based approach can give the right conditions for perfect competition which results in an efficient market. To achieve perfect competition many suppliers are required, each with an insignificant share on the market. Thus, no provider has the power to influence the price by changing its own offer. This is difficult to achieve in a reactive power market due to the local nature of reactive power, of which could result in a limited the number of providers in an area. There is instead a risk that node competition arises with a market-based approach [63] and result in an ability of participants to earn profit by altering price beyond the competitive level. Furthermore, the price of reactive power is based on the reactive power requirements in the system, which in turn depends on the system changes. If the market is not designed efficiently there is a risk of price volatility. The reactive power's localized nature can also affect the price and result in different prices in different zones or nodes [64].

5.1.2 Price structure and compensation

[64] is broadly categorizing reactive power market mechanism into two types, value-based and cost-based reactive power market. A value-based market is constructed on installed capacity of reactive power sources and the price (referred to as capacity-based) is therefore predetermined using long-term contracts [64]. The capacity-based price can

also be called availability cost or investment cost and includes the fixed amount of payment for the power plant to be available for reactive power provision [65].

In a cost-based market, the price structure is dependent on the performance of the reactive power source and based on the delivered energy which is in the need of the activation [64]. The price of this performance can be called energy-based price as well as utilization payment and is the compensation the provider gets for its utilization [65]. The cost of delivering reactive power for a provider is dependent on the operating loss and the opportunity cost. The operational cost includes the winding losses for reactive power generation or absorption. The opportunity cost occurs when the active and reactive power output are constrained by the generator's or converter's capability limit. Thus, the active power production needs to decrease in order to increase the reactive power output [60]. The compensation for the delivered energy is determined in short terms and therefore includes real needs on the grid. The operational and opportunity payment can thereby reflect the cost for of reactive power production better than availability payment which is determined in longer terms [63].

In order to calculate a reasonable payment for reactive power services, Expected Payment Function (EPF) in equation (12), is widely used in the literature, for instance in [64], [60] and [62]. The EPF includes the compensation for long- and short-term. Thus, the cost of being available for reactive power provision and the cost of delivering energy, which includes operational cost and opportunity cost.

$$EPF = Availability\ cost + Operation\ cost + Opportunity\ cost \tag{12}$$

The EPF is based on the reactive power capability curve in Figure 38.

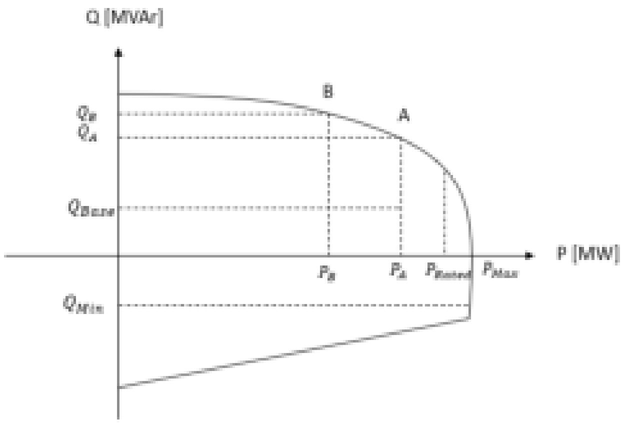

Figure 38. Reactive power capability curve for a synchronous generator.

From the grid codes a certain amount of reactive power production is mandatory and no payment is given, which is in the field between Q_{Base} and Q_{Min}. Furthermore, point A and B is different operating points. In the operating point (P_A, Q_{Base}) the generator can increase the amount of reactive power without reducing the amount of active power. In order to increase the reactive power production/absorption, the active power losses in the winding increases and therefore the expected payment is operation payment. If the system requires even more reactive power (from Q_A to Q_B), the production of active power has to be reduced from P_A to P_B. The reduction in active power payments must thus be compensated for in an equivalent reactive power market for the provider to want to decrease active power production [64]. With that said, EPF can be illustrated as Figure 39.

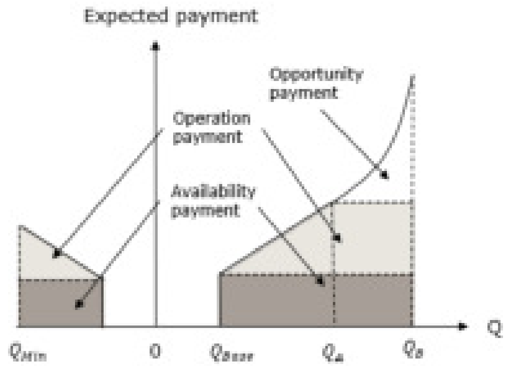

Figure 39. Illustration of the Expected Payment Function.

5.1.3 Contracting

As mentioned, a market design consists of two timeframes; long- and short-term. A long-term contract could be offered multi-year and in addition be complemented by annual year-ahead contracts. This kind of contracts is in the investment timeframe, with the purpose that providers invest in assets for reactive power source. In contrast, short-term contracts are operating at day-ahead and are aimed for providers that are unable to make long-term commitments [59]. WPPs are one type of provider where short-term contracts could be more beneficial than long-term contracts according to [34] and [66]. They argue that due to the high degree of variability of wind speed, it is difficult for a WPP to guarantee reactive power based on forecasted active power. The low availability could therefore result in difficulties signing long-term commitments. Therefore, WPPs needs to be considered as providers at a point where the availability becomes more certain, using short-term contracts.

A combination of long- and short-term contracts is recommended in [59] for several reasons. One main reason why it is unpreferable to have short-term contracts only is because it may not deliver the needed stability capacity, which in turn can result in security issues and extreme prices [59]. The short-term signal can in addition provide a small certainly to new providers [63]. A market with only long-term contracts can, on the other hand, result in a lack of capacity of reactive power source since it is difficult to predict the requirements years ahead and it is therefore a risk for over/under-procurements. By combined short-and long-term contracts, new CAPEX-heavy investments can be secured by long-term contracts, and at the same time providers that are not able to sign long-term contracts can contribute to the market. This means that with short-term contracts more providers can contribute to the market and the market power could decrease. Additionally, it does not matter at which point the contract is sign, it is rather the effectiveness of the reactive power resources that determines if a provider has a high ability to affect the price [59].

The mentioned compensations and contracts are used in market-based approaches. Svk presents two different regulated economic incentives with a belonging compensation method in [15]. The first method is grid tariffs designed in order to encourages provider to contribute with reactive power when needed in the system in longer terms. This incentive is paid based on Svk's costs for performing reactive power compensation under its own auspices. The second method is formed for shorter terms, in temporary or permanent form of voltage regulation. The compensation is administratively determined based on Svk's costs for performing temporary and permanent voltage regulation.

Figure 40 shows how a regulated and a market-based approach consisting of short- and long-term compensation.

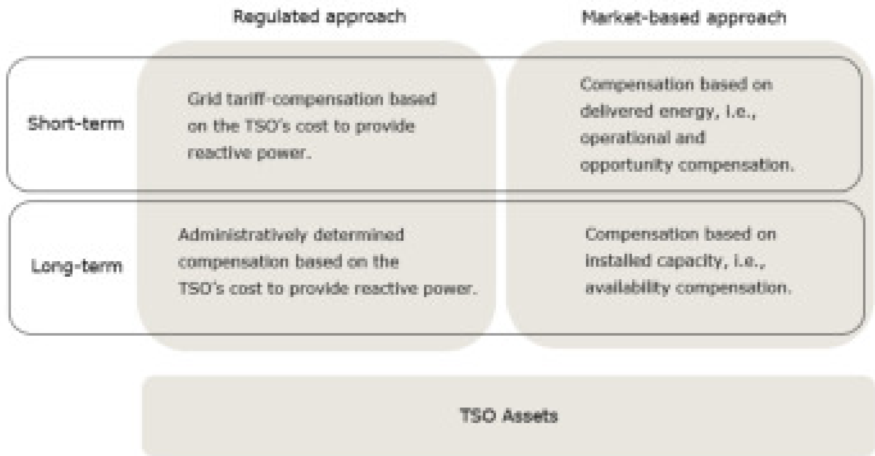

Figure 40. Different methods for providing reactive power compensation.

As seen in Figure 40, TSO assets (reactive power control techniques), is a different type of reactive power service. In 5.3 TSO assets are compared with a OWPP as a provider on a reactive power market.

5.2 Offshore wind as a provider in a reactive power market

In order for a OWPP to provide reactive power on a market it has to be profitable for the OWPP owner. At the same time, the main aim with the market is to stabilize the grid voltage. To achieve this, there are several aspects to consider. In the following section chosen aspects are discussed based on 5.1 and the simulations. The discussed aspects are mainly the cost of reactive power, the distance to onshore, and hence the reliability and the market power. Furthermore, a suitable market design for a OWPP is discussed.

5.2.1 Cost of reactive power

An OWPP as a provider in a reactive power market could differ from when a synchronous generator provides reactive power. Reactive power is cheap to produce for synchronous generators in comparison to active power, since no fuel is required [65]. Wind farms, on the other hand, do not save fuel cost by reducing its active power production and the opportunity cost should therefore reflect the revenue lost due to the nondelivered energy [34]. The reactive power capability curve in Figure 38 and the belonging Figure 39 of EPF concerns for a synchronous generator. For a wind power FSC, the operation cost for producing reactive power is generally low because no primary energy cost is needed. Furthermore, a FSC can generate reactive power while the active power generation is low [67]. There could therefore be an operation point C for an OWPP, as seen in Figure 41, where the active power production is close to zero.

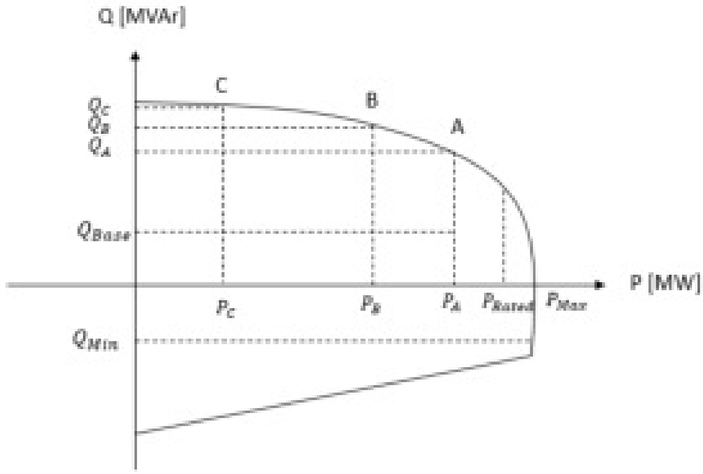

Figure 41. Reactive power capability curve for a theoretical offshore wind power plant.

In order for the OWPP to operate at (P_C, Q_C) and thus go from the operation point (P_B, Q_B), the active power production has to be further down-regulated, i.e., the OWPPs economic losses of active power will increase. That means that the opportunity cost must increase to create incentives for OWPP to down-regulate. The opportunity cost can be calculated, according to [66], by dividing the cost of active power loss with the increases reactive power according to equation (13). The durations of the calculations are one hour.

$$Opportunity\ price = \frac{Reduce\ of\ active\ power * electricity\ price}{Increase\ of\ reactive\ power} \tag{13}$$

Svk [9] has been estimating annual average electricity prices received per power plants in the future scenario ‘Electrification renewable’. In 2045 the annual average electricity price for OWPPs is estimated to 25 EUR/MWh in SE3. By using this electricity price, opportunity prices for reactive power production are estimated for the OWPP in the case study when $\frac{P}{P_n} = 0.4$, as shown in Figure 42. One EURO is assumed to be equal to 10 SEK.

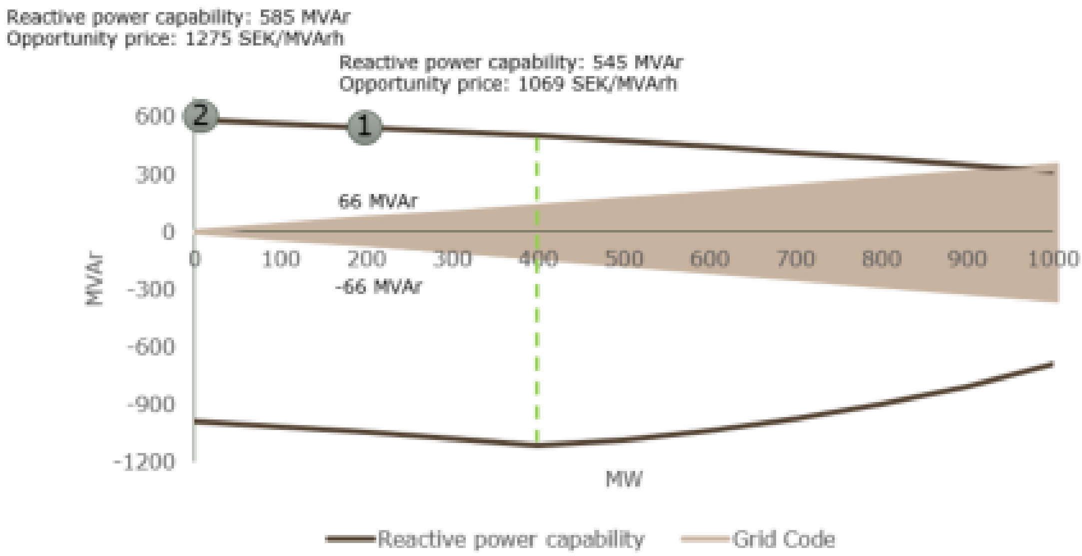

Figure 42. OWPP reactive power capability and opportunity price in comparison to the grid code in Sweden. The capability is determined at 1 p.u. voltage.

It is possible to determine that the more the OWPP down-regulate, the more the opportunity price increases. Further, according to [68], a maximum of 5 % of the annual active power production could be reduced in order to contribute with reactive power. Assuming full production 50 % of the annual hours [69], a total maximum loss of 175 200 MWh could occur. With Svk's estimated SE3 electricity price 25 EUR/MWh year 2045 for OWPPs, the annual sacrifice of active power could result in income losses corresponding to 4 380 000 EUR. In SEK this implies a loss of roughly 43 800 000 SEK/year for the OWPP owner. [68] illustrates the importance of compensate for this loss and implies that these compensations have the potential to be socio-economical advantageous in comparison with condensers and reactors (TSO assets). Hence, one important aspect to consider on a potential market is the alternative costs for the buyer of the reactive power – in this case the Swedish TSO. This aspect is considered further in Section 5.3.

5.2.2 Market design

A market for reactive power could be more towards a market-based approach or a regulated-based approach, and the market could also be nodal or zonal. If an OWPP would choose to down-regulate active power production in order to supply reactive power, it must be profitable for the owner. OWPPs market position and therefore profitability can increase or decrease depending on the market design. The type of contract can in turn have an impact on the profitability.

Firstly, zonal market could be advantageous for OWPP as it is a common price for the entire zone and market power can thus decrease. Moreover, the location of the node in a nodal market could have an impact on whether a zonal or nodal market is most advantageous for OWPP. If the node is placed close to POI, the simulations in Chapter 4 shows that the loss of reactive power in the OCS is small enough for OWPP to provide voltage stability onshore. The longer the distance, the larger could the losses potentially be.

On a regulated market, OWPPs could receive pre-determined compensation and thereby the incentives are guaranteed. However, a regulated approach is based on grid code requirements which are especially adopted to existing providers and not the future installed OWPPs. The pre-determined regulated compensations could therefore be based on the requirement rather than the farms' capability. This approach could therefore limit the OWPPs utilization, which is disadvantageous both for the OWPP owner and the TSO. This limitation is possible to see in the simulation as OWPPs capability is more utilized when simulating the grid code in GB, that is applied in POI, in comparison to the Swedish grid codes in POC (see Figure 28, Figure 29 and Figure 30). As has been said, it is cheap for OWPPs to produce reactive power, which means that they also could sell reactive power supply cheap on a reactive power market. In situations when there are a low wind speed and the OWPP has a low active power production, the owner could sell reactive power instead of taking the plant out of operation. In that way the owner potentially could earn more money, assuming that the compensation of the reactive power is higher than the cost of reactive power production. This could also create opportunities for the TSO to buy reactive power for a cheaper price in comparison if the compensation is pre-determined on a regulated market. Yet, it is difficult to forecast these situations and it may therefore be impossible to structure it in a long-term contract and therefore must happen during day-ahead. The OWPP could then bid a low tender depending on the situation at that time. The disadvantage of that is that the OWPP cannot expect to get this compensation. At a day-ahead market (short-term) there is a risk that OWPPs has a low market power and would therefore not winning bid as the production is more fare away than providers placed onshore. However, Figure 31 and Figure 32, primarily, is showing a high reliability as the reactive power production is stable in a wide range of active power production. The high reliability in combination with low reactive power losses in the OCS during low active power production, entails that there could be incentive for OWPP to down-regulate to increase their market power.

In Section 5.1.3, short-term contracts are described as the most suitable solution for WPPs because of the low availability certainly. However, the high OWPP reliability in Figure 31 and Figure 32 indicates that OWPPs reactive power capability and the forecasted active power production does not necessarily have to be combined. Because of that it could be possible to sign long-term contracts with OWPPs. It could be more beneficial with long-term contract for OWPPs considering the CAPEX-heavy investment. A long-term contract would be the market way to deal with the price-risks of the investments and with a contract the risks is divided on the producer and the buyer (the TSO in this case). Moreover, it could be beneficial for the TSO to sign long-term contracts with OWPPs as they make sure the farm is investing is the necessary equipment needed for supporting the onshore voltage stability. A comparison of long- and short-term contracts is presented in Table 12. However, it is of importance to consider the amount of reactive power reaching the onshore grid versus the amount that is being generated, which could impact the way the contracting is made and in turn the economic compensation. See Figure 31 and Figure 32 for representation.

Table 12. Advantages and disadvantages based on simulations and above analysis for a OWPP to sign long-term versus short-term contracts on a market.

	Long-term contract	Short-term contract
Advantages	Incentives for making CAPEX-heavy investments in needed equipment as compensation is guaranteed.	Possibility to sell reactive power cheap at low wind speed or down-regulate active power production when the current onshore needs are high.
Disadvantages	Risk for OWPPs to be under compensated because of the difficulties predicting reasonable pre-determined compensations years ahead.	Risk for OWPP to have a low market power and thereby not winning bids, i.e., low security for receiving compensation. Risk for price volatile.

5.3 TSO assets versus reactive power market

As seen in Figure 40, there are different methods of providing reactive power to the power grid. In the following section, TSO assets are compared with OWPPs as providers on a reactive power market. The comparison is based on the Sections 5.1 and 5.2 as well as the simulations.

In order to create possibilities for the upcoming changes in the energy system, certainly the increased share of WPPs, Svk [15] will secure operational reliability in short terms by install further TSO assets. The technology and cost development in the future will determine how the most operational reliable and cost-effective solutions will be shaped in longer terms. The interest of Svk [15] is to have a solution as socio-economic beneficial as possible. Svensk Vindenergi [68] means that compensated services of wind power probably can be the most advantageous socio-economic solution, in comparison with TSO assets.

In the theoretical Section 2.2.1, different reactive power control techniques (referred to as TSO assets) are presented. Synchronous Condensers and STATCOMs can provide reactive power services and have the ability to provide with inertia as well. An SVC, on the other hand, can provide fast response of reactive power control as a synchronous condenser, but cannot provide inertia. With that said, some TSO assets have additional stabilizing services except reactive power services, making them relevant for TSOs [25]. However, OWPP can likewise provide additional system-services with additional control methods and reprogramming of the converter, as explained in the theoretical Section 2.3.2. A reasonable compensation for the alternative cost must be given if the OWPP owner would invest in this upscaled version of the converter.

Voltage stability and cost efficiency for the TSO could differ depending on if a TSO asset or an OWPP provide reactive power. Firstly, the TSO could have a lack of control on a reactive power market due to the fact that they do not own the reactive power asset and the plannability reduces. The TSO might therefore have to adopt to the provider to reach the reactive power exchange needed. Thus, it is beneficial for the TSO to invest in TSO assets as they can place the assets where the need of the grid is the most essential. Additionally, the TSO have the ability of plan the production of a TSO asset. This results in a possible increase of voltage security.

Secondly, depending on the type of provider the degree of cost efficiency varies from the perspective of the TSO. Through a reactive power market, the economic incentives should motivate the provider to participate and therefore invest in the needed equipment. The TSO assets, on the other hand, have different costs of providing reactive power. Generally, the investment cost (CAPEX) of the assets is higher than the operational cost (OPEX) [70]. By using a market for reactive power, the TSO does not pay for the CAPEX price but has to buy reactive power from provider, in this case an OWPP. When considering a OWPP as a provider the lost income during down-regulation has to be considered. As seen in Figure 42, the more the OWPP down-regulate, the more increases the opportunity cost. Additionally, OWPP has to reduce the annual active power production with 5 % in order to provide reactive power services, which would result in a loss of 43 800 000 SEK/year for the OWPP in the case study.

OWPP’s effectiveness to provide reactive power is affected by the distance between the OWPP and the onshore grid and is therefore most likely less effective than for assets placed onshore. Figure 33 and Figure 34 is showing that the OWPP has to produce/absorb more reactive power than the shunt to reach the same voltage level at POI, due to the behavior of the OCS. When considering the mentioned aspects, it could be the most cost beneficial for the TSO to invest in TSO assets than compensate a OWPP for providing reactive power.

6. Discussion

In this thesis, the capabilities and possibilities for a OWPP to contribute to voltage stability through reactive power compensation have been investigated. The focus has been on technical capabilities, grid codes and economic incentives, from the perspective of the TSO and wind farm owner. In the following paragraph of this section key results from the literature study, case study and the market opportunity analysis are shortly presented in order to further discuss them.

The grid code literature study indicates that the Swedish grid codes for OPPMs are not as strict or same level of details as in Great Britain and Denmark – two countries with a higher amount of offshore WTs compared to Sweden. Furthermore, simulation results show a high reliability of reactive power from the 1000 MW OWPP, independent on the active power production tested. The OWPP had higher reactive power capabilities in cases of over- as well as under-volage found onshore, compared to the Swedish grid code requirements. Yet, the distance from the OWPP to the onshore grid and the OCSs impact cannot be neglected, as it affects the amount of reactive power that can be transferred to the onshore power grid. Simulations also demonstrate that, comparing to a shunt placed onshore, the needed reactive power production from the 1000 MW OWPP for voltage stability is higher. In turn, the market opportunity analysis indicates that a market-based approach using a combination of short- and long-term contracts could be beneficial for the 1000 MW OWPP, as well as for the TSO. Finally, due to the distance impact, a zonal pricing would be beneficial for the OWPP as it could reduce the risk of market power in the market area.

As stated, the simulation results indicate that the OCS has a rather considerable impact of the reactive power capability of the wind farm. The design of the OCS is therefore affecting the outcomes. Different transformer settings could change the inductive behavior of the OCS as well as a changed cable design and the number of cables could affect the capacitive behavior. Consequently, the theoretical capability of the 1000 MW OWPP is higher than the amount of reactive power that could be simulated due to the system behavior. The inductive or capacitive behavior of the OSC affects the FSC, since it acts as a terminal, balancing the need from the grid with the turbine behavior. One alternative method for making the power flow simulations, and at the same time potentially decrease the OCS impact, would have been changing the load onshore gradually, instead of using a fixed value for each scenario. For instance, the OWPP had occasionally difficulties to reach the maximum grid code requirement at full active power production even though the capability curve technically allowed it. In turn, another dimensioning of the FSC could have been needed to reach the sufficient value of reactive power. Subsequently, the design of the FSC was more important than expected, affecting the resulting capability considerably.

Furthermore, one indication is that the grid codes available for OPPMs in Sweden are not taking fully advantage of the potential capability of Type 4 OWPPs, especially not at lower active power productions. At very low active power production, neither seem the grid codes of Denmark and GB according to the results. However, an increased usage of the capability could befit the voltage stability of the power grid in a greater occurrence, taking notes from the Danish grid code especially.

However, grid codes cannot be decided anyhow in order to make the impact on the grid increase. Thus, it is of great importance to compose the requirements in the right extent. At low active power loads, a possibility is to increase the reactive power requirement, which would be the most efficient and safe way for a TSO. Yet, it is central to investigate the potential compensation for the OWPP to contribute with such services since, for instance, certain dimensions of the converter, as seen in the sensitivity analysis, is needed. A small, yet considerable, increase of reactive power requirements could make the potential economic compensation for the TSO lower in comparison with using today's grid code. An example is from the simulations where the TSO probably would choose the reactive power from the shunt since a lower amount of reactive power is needed for voltage stability. However, with stricter grid codes, the TSO could buy reactive power services from the OWPP cheaper in comparison with today's grid codes, and the farm owner would be compensated as well. The question is if the compensation is enough for the owner, making the right incentive for additional services as well as equipment. To achieve the future wind utilization, stricter grid codes and incentives have to be clearly stated in order for OWPP owners to invest in converters able to contribute with system services. The following question is therefore important to consider further for every specific OWPP in the future: How large has the compensation to be in order to cover expenses for necessary equipment and potential down-regulation of active power production?

As the 1000 MW OWPP is showing a high reliability of reactive power production, it would therefore be able to sign both short- and long-term contracts. Yet, as the OWPP in this case study is a fictitious farm, the same reliability cannot be expected for the upcoming OWPPs in Sweden. Other studies, [34] and [59], are showing that OWPPs have a low reactive power reliability, which indicates, in contrast to the analysis of this research, that they are not able to sign long-term contracts. As there is no market for reactive power today and the OWPP technology of the future is not fully developed, the outcomes of different contracts are hard to predict as well as the ability signing the contracts.

Even though that the two aspects *market-based approach* and *TSO assets* have been compared in this research, no analysis has been made considering a combination of the two. Since large reactive power resources and services potentially will be needed in the future, there could be a risk that TSO assets or a market approach only could not cover the total need. A combination could conceivably be the most socio-economic profitable. Furthermore, a zonal pricing could be beneficial for a reactive power market as it could limit the risk of market power. With the previously mentioned combination, the risk of TSO assets having a large market share is difficult to avoid due to the conscious placement to provide reactive power at especially needed nodes. Additionally, onshore WPPs could have a larger market power than OWPPs as well, because of the distance. A market-based approach may therefore not necessarily have to be the most effective solution for ensuring voltage stability, due to the local nature of reactive power.

6.1 Future research

In order to investigate a reactive power market in Sweden, the zonal aspect should be considered further. Different zones have different need of reactive power compensation and would therefore impact the potential market situation of an OWPP. It is possible to determine a changing situation in the areas where nuclear power plant have been decommissioned in Sweden, of which could result in variating needs of reactive power in the future as well due to the plan of decommissioning all nuclear power plants. Furthermore, advantages and disadvantages with a regulated approach should be further investigated in order to compare that market outcomes with a market-based approach.

Moreover, as results from this research as well as [34] shows, another important aspect to consider in a greater extent is the dimension of the FSC. For instance, the FSC impact on OWPP expenses and in turn a potential economic compensation on a market. As stated in the discussion, the needed compensations for different OWPPs have to be evaluated further to ensure the socio-economical outcome of a reactive power market as well as profitability for the OWPP owners.

In addition, a meshed offshore power grid could be considered. In this research, a simple offshore “point-to-point” connection have been evaluated for the OWPP. Since Svk have not yet presented the potential structure of the offshore transmission system, it is unknown how the outcome will be. A meshed offshore grid would certainly have different power flows and several OWPPs connected, and therefore the OWPP behavior and voltage impact could differ in comparison with the results from this thesis.

Finally, other interesting aspects to consider would be a DSO perspective and dynamic simulations, testing short-term voltage stability impact as well.

7. Conclusions

- The 1000 MW OWPP in the case study shows high inductive and capacitive capability for a wide range of active power production.

- The 1000 MW OWPP shows a higher reactive power capability than the grid codes require. A further utilization of the OWPP could be achieved with stricter grid codes, yet stricter grid codes have to be complemented with the right economic incentives in order for the OWPP owner to invest in the needed equipment.

- Due to the distance impact, OWPPs possibilities to contribute, and get compensation for the additional service, is dependent on the competition with assets onshore. Due to this, local reactive power attributes of specific zones have to be evaluated. However, the possibilities for the 1000 MW OWPP to contribute to local voltage stability onshore is considered as good, as a sufficient amount of reactive power could reach the onshore power grid.

- A beneficial market design for OWPPs should include the possibility of guarantee long-term economic incentives as well as create the possibility to sell reactive power during low wind speeds or high reactive power demands by down-regulate the active power production. It could be socio-economic beneficial for the TSO as capacity could be secured in longer and shorter timeframes, yet it is hard to predict as the market design will be compared with TSO asset expenses.

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Appendix

Appendix A

R-Studio code used for plotting reactive power capability curve

```
install.packages("tidyverse")
library(tidyverse)

RePowerCap <- function(P, V_LV, Ic=1.25, Vmax=1.1, Vmin=0.8, X=0.156+0.035
R=0.015+0.022, B=0.062){
QVinj <- sqrt((((V_LV*Vmax)/sqrt((R^2)+X^2))^2) - ((P+(( (V_LV^2)*R) /
((R^2)+X^2))))^2) -(V_LV^2*X)/((R^2)+X^2)
QVabs <- sqrt((((V_LV*Vmin)/sqrt((R^2)+X^2))^2) - ((P+(( (V_LV^2)*R) /
((R^2)+X^2))))^2) -(V_LV^2*X)/((R^2)+X^2)

QIinj <- sqrt(((V_LV*Ic)^2)-P^2)
QIabs <- -sqrt(((V_LV*Ic)^2)-P^2)

Qmax <- min(QVinj,QIinj)+B*V_LV^2
Qmin <- max(QVabs,QIabs)+B*V_LV^2

  return(c("Qmax"=Qmax,"Qmin"=Qmin,"V"=V_LV,"P"=P))
}

tmp <- rep(seq(0,1,by=0.1),5)
tmp1 <- rep(seq(0.9,1.1,by=0.05),each=11)

Q <- as.data.frame(t(mapply(RePowerCap,P=tmp, V_LV=tmp1)))
Q

Q$V <- as.factor(Q$V)
Q$P <- as.factor(Q$P)

p0<- ggplot(data=Q,)+

  geom_line(aes(x=P,y=Qmax,colour=V,group=V,linetype="longdash"))+
  geom_line(aes(x=P,y=Qmin,colour=V,group=V,linetype="solid"))+
  ylab("Q")+
  scale_linetype_discrete(name="Q",

                        breaks=c("longdash", "solid"),
                         labels=c("Inj", "Abs"))

p0
```

Appendix B

MATLAB code used for verification of the offshore connection system - Cable

```
% HVAC Transmission cable parameters:
C_input=0.17*10^-6*20; %F
L_input=0.4*10^-3*20;  %H
R_input=0.0246*20;      %ohm (AC 20degrees)

X=j*2*pi*50*L_input     %ohm
B=j*2*pi*50*C_input     %S
Z=R_input+X
Y=B

%Calculate A,B,C,D
A_m=(Y/2)*Z+1;
B_m=Z*((Y/4)*Z+1);
C_m=Y;
D_m=(Y/2)*Z+1;
ABCD=[A_m B_m;C_m D_m];

%Receiving side input
Pr=494.23*10^6;
Qr=-28.9*10^6;
Vr=218.28*10^3;
Ir_h=Pr/Vr;                 %main current
Ir_f=Ir_h/sqrt(3)           %phase current
Rec=[Vr;Ir_h];

%Calculate sending side
Send=ABCD*Rec;
Vs=Send(1);
Is_h=Send(2);               %main current
Is_f=Is_h/sqrt(3);          %phase current
Is_f_mag=abs(Is_f)
Vs_mag=abs(Vs)
Vs_angle=angle(Vs);
Ps=real(Vs*conj(Is_h))
Qs=imag(Vs*conj(Is_h));
Q_netto=Qs-Qr
```

MATLAB code used for verification of the offshore connection system - Transformer OSS

```
%Per unit bases:
Sbase=1000*10^6; %VA
Vbase=66*10^3;   %V
Zbase=Vbase^2/Sbase;
Ybase=1/Zbase;
%Trafo OSS Z
Zpu=0.005*(350/500)+0.16*(350/500)*i %pu
Z=Zpu*Zbase;
%Trafo OSS core (Y):
Rc=600*(350/500); %pu
Xm=400*(350/500); %pu
Gc=1/Rc;
Bm=1/Xm;
Ypu=Gc-Bm*i
Y=Ypu*Ybase; %Ym
%Calculate A,B,C,D
A_m=(Y/2)*Z+1;
B_m=Z*((Y/4)*Z+1);
C_m=Y;
D_m=(Y/2)*Z+1;
ABCD=[A_m B_m;C_m D_m];
%Receiving side input
Pr=496.75*10^6;
Qr=9.41*10^6;
Vr=219.51*10^3;
Ir_h=Pr/Vr;              %main current
Ir_f=Ir_h/sqrt(3)        %phase current
Rec=[Vr*(66/220);Ir_h*(220/66)];
%Calculate sending side
Send=ABCD*Rec;
Vs=Send(1);
Is_h=Send(2);            %main current
Is_f=Is_h/sqrt(3);       %phase current
Is_f_mag=abs(Is_f)
Vs_mag=abs(Vs)
Vs_angle=angle(Vs);
Ps=real(Vs*conj(Is_h))
Qs=imag(Vs*conj(Is_h));
Q_netto=Qs-Qr
```

MATLAB code used for verification of the offshore connection system - Transformer OnSS

```
%Per unit bases:
Sbase=1000*10^6;   %VA
Vbase=220*10^3;    %V
Zbase=Vbase^2/Sbase;
Ybase=1/Zbase;
%Trafo OnSS Z:
Zpu=0.003*(640/1000)+0.16*(640/1000)*i; %pu
Z=Zpu*Zbase;
%Trafo OnSS core (Y):
Rc=800*(640/1000); %pu
Xm=500*(640/1000); %pu
Gc=1/Rc;
Bm=1/Xm;
Ypu=Gc-Bm*i;
Y=Ypu*Ybase; %Ym
%Calculate A,B,C,D
A_m=(Y/2)*Z+1;
B_m=Z*((Y/4)*Z+1);
C_m=Y;
D_m=(Y/2)*Z+1;
ABCD=[A_m B_m;C_m D_m];
%Reciving side input:
Pr=984.63*10^6;
Qr=46.83*10^6;
Vr=395.95*10^3;
Ir_h=Pr/Vr;            %main current
Ir_f=Ir_h/sqrt(3)      %phase current
Rec=[Vr*(220/400);Ir_h*(400/220)];
%Calculate sending side
Send=ABCD*Rec;
Vs=Send(1);
Is_h=Send(2);          %main current
Is_f=Is_h/sqrt(3);     %phase current
Is_f_mag=abs(Is_f)
Vs_mag=abs(Vs)
Vs_angle=angle(Vs);
Ps=real(Vs*conj(Is_h))
Qs=imag(Vs*conj(Is_h));
Q_netto=Qs-Qr
```

Tables of the **verification of the offshore connection system**

Table 13. Verification of a cable.

		Simulated values	Calculated values	Difference [%]
Receiving side	Vr [kV]	218,28	-	-
	Pr [MW]	492,23	-	-
	Qr [MVAr]	-28,9	-	-
	Ir [A]	1309,47	1307,20	0,17
Sending side	Vs [kV]	219,51	219,17	0,15
	Ps [MW]	496,75	496,76	0,00
	Qs [MVAr]	-9,41	-9,33	0,90
	Is [A]	1396,80	1312,40	0,43

Table 14. Verification of a transformer in the OSS.

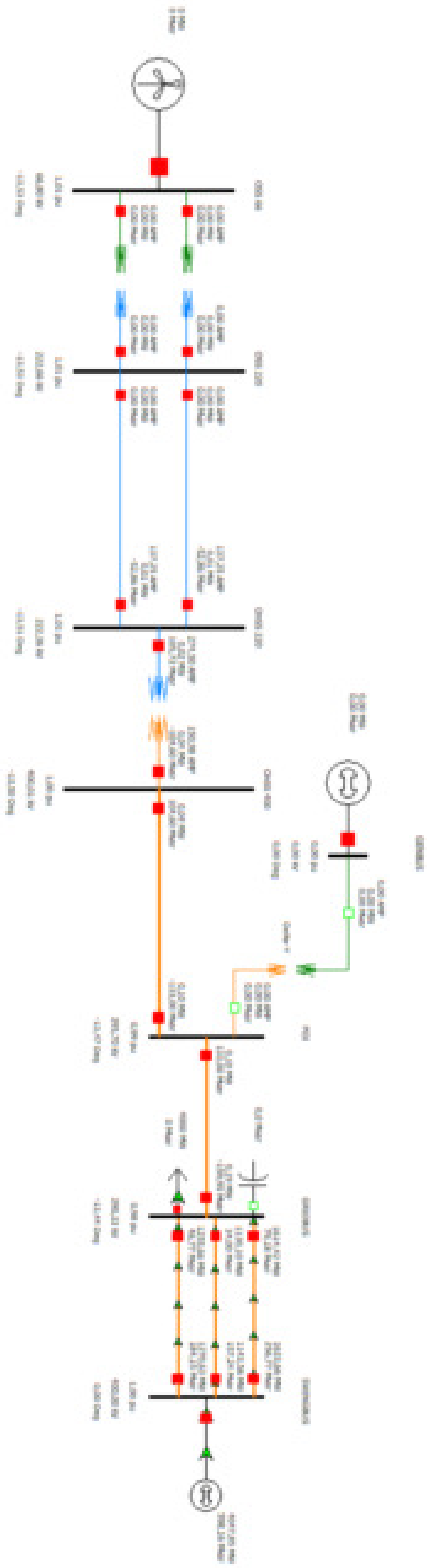
		Simulated values	Calculated values	Difference [%]
Receiving side	Vr [kV]	219,51	-	-
	Pr [MW]	496,75	-	-
	Qr [MVAr]	9,41	-	-
	Ir [A]	1306,8	1306,50	0,02
Sending side	Vs [kV]	66	66,10	0,13
	Ps [MW]	500	500	0,00
	Qs [MVAr]	21,93	22,10	0,57
	Is [A]	4378,07	4376,90	0,03

Table 15. Verification of a transformer in the OnSS.

		Simulated values	Calculated values	Difference [%]
Receiving side	Vr [kV]	395,95	-	-
	Pr [MW]	984,63	-	-
	Qr [MVAr]	46,83	-	-
	Ir [A]	1437,37	1434,7	0,12
Sending side	Vs [kV]	218,28	219,38	0,50
	Ps [MW]	988,46	988,46	0,00
	Qs [MVAr]	57,80	57,78	0,04
	Is [A]	2618,94	2615,90	0,12

Appendix C

Final representation of the test system in PowerWorld Simulator



Appendix D

Simulation results

Table 16. Case: Grid code in POC.

Case	OWPP production [MW]	OWPP production [MVAr]	Q in POI (GC) [MVAr]	Voltage at POI [p.u.]
A1	0	0	140,53	1,02
	200	-64	62,49	1,01
	500	-148	-96,95	0,99
	800	-120	-198,00	0,97
	1000	-30	-211,49	0,97
A2	0	0	156,69	1,07
	200	-64	79,14	1,06
	500	-150	-76,39	1,04
	800	-220	-304,71	0,99
	1000	-130	-315,28	0,99
B1	0	0	119,76	0,94
	200	68	179,83	0,96
	500	167	223,13	0,97
	800	228	177,27	0,97
	1000	294	142,16	0,96
B2	0	0	93,36	0,83
	200	69	154,26	0,86
	500	182	203,40	0,89
	800	307	209,4	0,90
	1000	395	186,131	0,90

Table 17. Case: Grid code in POI.

Case	OWPP production [MW]	OWPP production [MVAr]	Q in POI (GC) [MVAr]	Voltage at POI [p.u.]
A1	0	-130	0	1
	200	-225	-120	0,98
	500	-320	-330	0,95
	800	-210	-330	0,95
	1000	-105	-330	0,95
A2	0	-114	0	1,05
	200	-237	-120	1,03
	500	-340	-330	0,99
	800	-235	-330	0,99
	1000	-140	-330	0,99
B1	0	-110	0	0,92
	200	225	330	0,98
	500	279	330	0,99
	800	379	330	0,99
	1000	472	330	0,99
B2	0	-85	0	0,81
	200	254	330	0,89
	500	314	330	0,91
	800	427	330	0,92
	1000	530	330	0,93

Table 18. Case: Reactive power capability.

Case	OWPP production [MW]	OWPP production [MVAr]	Q in POI [MVAr]	Voltage at POI [p.u.]
A1	0	-310	-218,00	0,96
	200	-330	-258,76	0,96
	500	-320	-329,52	0,95
	800	-290	-475,61	0,92
	1000	-190	-496,79	0,92
A2	0	-380	-293,62	1
	200	-400	-336,19	0,99
	500	-380	-391,20	0,98
	800	-350	-538,64	0,95
	1000	-240	-529,7	0,95
B1	0	245	359,83	0,98
	200	230	337,89	0,98
	500	215	271,18	0,98
	800	220	168,63	0,97
	1000	235	73,11	0,95
B2	0	400	469,82	0,91
	200	365	433,32	0,91
	500	335	352,94	0,91
	800	335	239,19	0,90
	1000	355	139,47	0,89

Table 19. Case: Shunt compensation. The OWPP production in MVAr is from the case grid code in POC.

Case	OWPP production [MW]	OWPP production [MVAr]	Shunt production [MVAr]	Q in POI [MVAr]	Voltage at POI [p.u.]
A1	0	0	-898,6	125,5	0,96
	200	-64	-812,8	47,47	0,96
	500	-148	-593,2	-115,23	0,95
	800	-120	-625,2	-235,15	0,92
	1000	-30	-621,3	-267,67	0,92
A2	0	0	-919,4	135,17	1
	200	-64	-909,1	55,8	0,99
	500	-150	-676,9	-103,74	0,98
	800	-220	-477,9	-317,69	0,95
	1000	-130	-337,8	-361,77	0,95
B1	0	0	558,9	130,1	0,98
	200	68	321,6	186,3	0,98
	500	167	189,9	228,32	0,98
	800	228	91,2	181,38	0,97
	1000	294	-	-	-
B2	0	0	721,4	111,95	0,91
	200	69	474,4	167,51	0,91
	500	182	235,7	212,89	0,91
	800	307	38,8	212,04	0,90
	1000	395	-	-	-