Design of a reactive power compensation scheme for AC offshore wind power systems

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Abstract - To maintain a stable power system, even with the growing integration of inverter-based renewable sources, grid codes require that all plants possess sufficient dynamic reactive power capability to support the grid voltage. For offshore wind farms, which are situated far from shore, the reactive power support cannot be based on the wind converters, and therefore the capability requirement must be fulfilled from equipment installed onshore. The plant must also manage its own reactive power production, which can be significant because of the long transmission distances and large wind farm sizes.

This paper presents an approach for designing an optimized plant power system for compensating the AC transmission system in offshore wind farms and complying with the reactive power capability of the grid codes. This approach makes use of different power system components such as shunt reactors and STATCOMs for a cost-effective design. The approach shows how to determine the relative size of the compensation equipment and methods to verify the requirements as given in the grid codes involving PQ and UQ plots. The approach is also demonstrated for a synchronous condenser.

Index Terms — Offshore wind, AC transmission, grid codes, reactive power compensation, PQ plot, UQ plot.

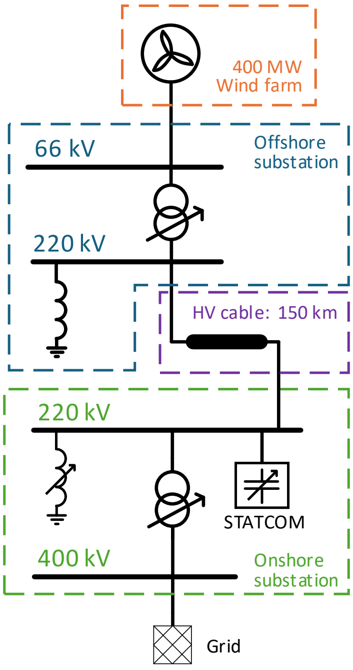


Fig. 1 AC-connected offshore wind farm system.

I. INTRODUCTION

Planning an AC-connected offshore wind farm system, such as the wind farm shown in Fig. 1, presents significant challenges with the management of the reactive power, particularly for remote offshore wind farms. The following sections presents these challenges and the basis for the reactive power compensation scheme.

A. Reactive power from the transmission cable

The long HV transmission cable produces significant amounts of reactive power. If not compensated, all the reactive power will flow to the grid causing problems both internally in the wind farm transmission system and externally to the connected grid. Internally, the transmission cable will get overloaded on the onshore side, and there will be a large voltage rise across the onshore transformer. Externally, the same challenges with overloading and voltage rises will occur in the grid, effectively putting the burden on the grid owner to consume the reactive power. Indeed, this is why the grid sets conditions for the reactive power exchanged in the interface point. Ultimately, the reactive power must be consumed locally and preferably close to the source of the reactive power.

B. Variation of reactive power with the wind power production

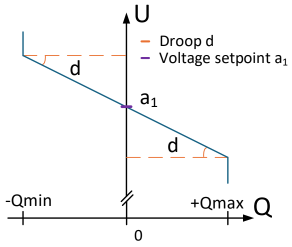
The reactive power produced in the wind farm system varies with the active power transmitted. When the active current from the wind farm flows through the inductive components of the transformers and the HV transmission cable, an inductive reactive power is created which neutralizes some of the reactive power produced in the cable. This suggests that the reactive power compensation scheme cannot be of a fixed size but must act according to the power produced.

C. Grid requirements to the reactive power

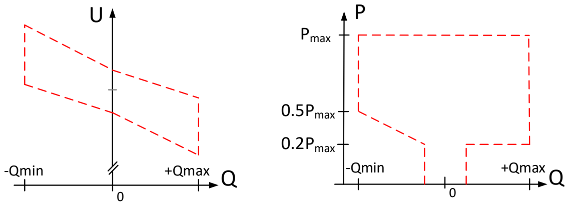
As mentioned, the grid owner typically sets requirements for the reactive power in the grid connection point. These conditions are often specified so that the reactive power from the wind farm will support the voltage in the grid. An example is shown in Fig. 2 which shows the grid code requirements in the United Kingdoms (UK) [1]. Similar codes exist for other countries [2]. Fig. 2a) shows the required voltage support characteristics. The droop and voltage setpoints are specified within given ranges by the operator during operation. To comply with all possible setpoints for all operating voltages in Fig. 2a), the plant must, as a minimum, provide the capability as shown in the UQ plot in Fig. 2b).

The UQ capability is specified for the maximum active power production. The same capability requirement can also be requested for all levels of active power production, but usually some relaxation is given for low active power production. The capability required at various levels of active power production is captured in a PQ plot as shown in Fig. 2c). It is seen that, for the UK, the required inductive reactive power between 20% and 50% of the full active power production reduces linearly with the active power production. Further relaxation to the capability is given below 20% where no capability is specified and the plant should provide only what it's capable of at that production level.

It is important to note that the curves given in Fig. 2 applies to the wind farm system as a whole and not to any individual equipment of the plant. For example, it is not sufficient to adopt these requirements directly to voltage support equipment such as a STATCOM as there might be excessive reactive power from the system which alters the overall performance. The maximum active power P_{max} is not the active power produced at the WTG terminals, but the maximum active power flowing in the grid interface point. Q_{min} and Q_{max} corresponds to power factor limits specified at P_{max}. In the UK a power factor limit of 0.95 is used.



a) Voltage support characteristics



b) UQ plot c) PQ plot

Fig. 2 Q requirements at grid interface point, UK [1].

D. Basis for compensation scheme

The preceding discussion shows that the management of the reactive power is twofold:

I. To compensate the reactive power produced internally in the system, which varies with the wind power production.
II. To provide reactive power to external systems according to the dynamic voltage support requirements given in the grid codes.

Both objectives address the control of reactive power. However, they differ in how quickly the management must be achieved. Full voltage support must be achieved typically within 1 or 2 seconds, but the variation in the reactive power resulting from changes in the wind is much slower. Consequently, while fast-acting compensation equipment is required for the stricter voltage support requirements, slower and cheaper equipment can be used for compensation of the reactive power internally in the system. This will be the basis for optimizing the reactive power compensation scheme in this paper.

In this paper shunt reactors are proposed to achieve the slow regulation required for objective I. The shunt reactors are equipped with on-load tap changers (OLTCs) to address the variability of the reactive power. Switching of each tap typically requires a few seconds. It is further assumed, for the sizing according to objective II, that the change in the wind is slow enough for the system to be considered sufficiently compensated by the shunt reactor OLTCs prior to a grid voltage step.

As a baseline, a STATCOM has been considered to provide the voltage support of objective II. A STATCOM can typically provide its full output within hundreds of milliseconds. For the reactive power scheme of this paper, a static var compensator (SVC) would also provide the same functionality as a STATCOM. However, for simplicity, this paper only considers the use of a STATCOM.

This paper presents a procedure for determining the relative sizes of the equipment in the compensation scheme to comply with objectives I and II. The procedure aims to minimize the size of the STATCOM, which is considered the most expensive equipment. It is also shown how the scheme can be altered to fit equipment with asymmetrical reactive power capability such as a synchronous condenser.

II. EXAMPLE SYSTEM OF AN AC-CONNECTED OFFSHORE WIND FARM

An example offshore wind farm system based on Fig. 1 is considered to demonstrate the compensation scheme presented in this paper. The following sections provide details on the parameters used to model this system.

A. System layout

The system consists of an offshore wind farm of 400 MW represented by a single source connected to a 66 kV switchgear on an offshore substation. Through an offshore transformer the substation is connected to a 150 km long AC transmission cable to transmit the wind power to the grid connection onshore. There is a substation onshore to receive the transmitted power and provide the necessary reactive power compensation. Finally, an onshore transformer steps the voltage to the level of the grid connection.

Equipment to compensate the reactive power is placed both onshore and offshore. There is one shunt reactor on each end of the cable to compensate the cable. The STATCOM is placed onshore. The details of the compensation equipment are determined in chapter III. The following sections provide more details on the transmission equipment in the example system. Typical data have been used.

B. Offshore wind farm

Typically, the wind farm consists of several strings of wind turbine generators (WTGs) connected radially with inter-array cables. However, the internal workings of the offshore windfarm are not of relevance to the transmission system and the reactive power compensation scheme. The wind farm is therefore modeled as a single source of power in this paper.

The active power produced from the source represents the active power produced from all the WTGs. It is assumed that this source produces zero reactive power. This assumption is valid for type 4 WTGs which are connected to the system with full scale converters. The converters can be used to compensate for the reactive power produced in the inter-array cables. Technically, the WTGs could be used to compensate the transmission cable as well. This would reduce or remove the need for an offshore shunt reactor depending on the size of the WTG converters. If the WTGs are used for this purpose, it must be verified that the offshore transformer rating is sufficient to handle both the maximum active power production and the reactive power compensation from the WTGs.

C. AC transmission cable

The parameters used for the transmission cable are shown in TABLE I. There might be thermal bottlenecks in the cable depending on the environment the cable is installed in. In addition, there will be a higher current loading at the cable ends due to the flow of reactive power produced by the cable. To cater for varying ampacities and loadings, typically the transmission cable is divided into sections of different cross-sections and materials to optimize the cable design. However, for demonstration of the reactive power compensation scheme, any cable representing a production of significant reactive power is sufficient. Therefore, for simplified analysis, the same cable type has been considered throughout the cable.

TABLE I
TRANSMISSION CABLE PARAMETERS

Parameter	Value	Unit
Length	150	km
Resistance	0.035	Ω/km
Reactance	0.11	Ω/km
Capacitance	0.22	$\mu\mathrm{F}/\mathrm{km}$

D. Transmission transformers

The parameters used for the transmission transformers are shown in TABLE II. The transmission voltage considered for this example system is 220 kV. The selection of the transmission voltage is a trade-off between the reduction of the active current produced by the offshore wind farm (using high transmission voltages) and minimizing the charging current of the transmission cable (using low transmission voltages). The transformers step up the voltage from 66 kV on the offshore substation, to 220 kV in the transmission cable, and to the grid voltage level, here assumed as 400 kV.

Each transformer is equipped with an OLTC. The offshore transformer is set to control the offshore 66 kV bus while the onshore transformer is set to control the onshore 220 kV bus. The tap range of the onshore transformer is set according to an expected grid voltage variation of ±10%. The tap range of the offshore transformer is set so that a nominal voltage on the 66 kV bus always can be achieved as long as the voltage at the 220 kV bus is at the nominal voltage.

TABLE II
TRANSFORMER PARAMETERS

Parameter	Unit	Offshore	Onshore
Rated power	MVA	450	450
Rated voltage	kV	66/220	220/400
Impedance	%	12.5	12.5
X/R	-	40	40
Tap changer	-	OLTC, HV	OLTC, HV
Tap range	%	±5	±10

III. PROCEDURE FOR SIZING OF THE REACTIVE POWER COMPENSATION SCHEME

In this chapter the procedure for determining the equipment ratings of the reactive power compensation scheme is presented. First the reactors are sized to compensate the reactive power generated internally in the system. Then, the STATCOM is sized to comply with the voltage support requirements of the grid code.

A. Offshore reactor sizing

A fixed shunt reactor is placed offshore to draw some of the reactive power offshore. This improves the current distribution of the cable. The highest current loading is during full wind power production. The offshore reactor is sized to achieve equal current at each end of the cable during full production. A shunt reactor rated for 180 MVAR gives the current distribution in the cable as shown in Fig. 3. In the figure 0 km is at the offshore end and 150 km is at the onshore end.

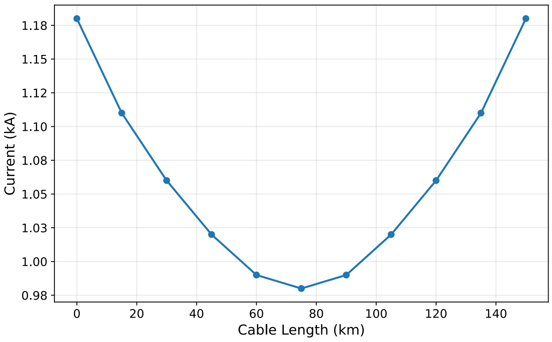


Fig. 3 HV cable current distribution at full production.

B. Onshore reactor sizing

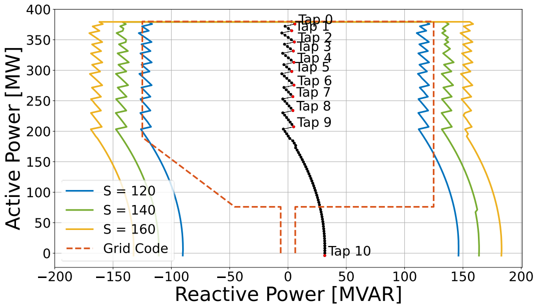
The onshore reactor is equipped with an OLTC to compensate for the varying reactive power production in the wind farm system during operation. The OLTC is set to regulate the reactive power in the grid interface point to 0 MVAR. During voltage support, the STATCOM is also regulating the reactive power in the grid interface point according to the voltage support characteristics of Fig. 2a). To prevent the STATCOM and shunt reactor from competing during operation, the shunt reactor control is configured to regulate as if the STATCOM was not present. This is achieved by subtracting the reactive power contribution from the STATCOM in the shunt reactor control loop. Tap steps of 10 MVAr are considered.

The minimum shunt reactor tap is determined based on when the system is producing full wind power. The reactive power produced in the system is then at its lowest. From a load flow calculation at full wind power production, a minimum tap of 190 MVAr is found sufficient to achieve 0 MVAr in the grid interface point.

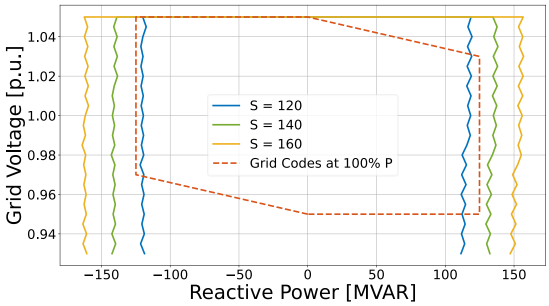
The maximum tap can be determined based on when the system has no active power production. However, in the UK grid codes, the capability requirement at lower active power production is relaxed. The point where the relaxation starts (50% of P_{max} for the UK as seen in Fig. 2c)) can often be used for determining the shunt reactor maximum tap. Using this approach, the maximum tap will be lower which gives an overall lower shunt reactor rating. From a load flow calculation at 50% of maximum active power production, it is determined that a maximum tap of 290 MVAr is sufficient to achieve 0 MVAr in the grid interface point.

The black curve in the center of Fig. 4a) shows the reactive power regulated by the wind farm system with only the reactors connected (no STATCOM). In accordance with the design, it is seen that the control target of 0 MVAr with a ±5 MVAR deadband is reached between 50% to 100% power production. The figure indicates the points where a new shunt reactor tap position is required (when sweeping from 0% to 100%). For lower active power production, the maximum shunt reactor tap is reached and the surplus reactive power from the wind farm system flows to the grid when there is no STATCOM.

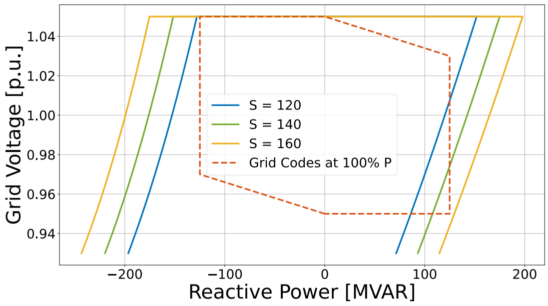
Finally, it can be noted that the shunt reactors can be used to compensate for other sources of reactive power. For example, often harmonic filters are installed to comply with harmonic limits, and these filters generate significant reactive power. The generation, however, does not vary during operation and can be accounted for by increasing the shunt reactor rating.



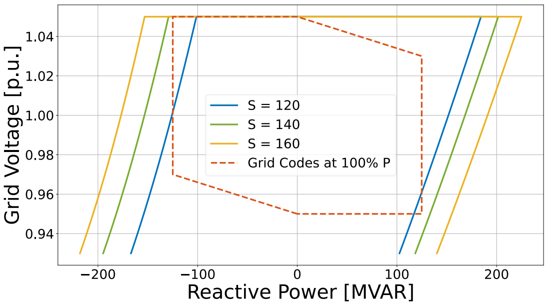
a) PQ plot



b) UQ plot



c) Dynamic UQ plot – Step down



d) Dynamic UQ plot – Step up

Fig. 4 Wind farm reactive power capability.

C. STATCOM sizing

A STATCOM rating is selected to cover the capability curves of Fig. 2. The capability is verified by recording the system capability for several load flow scenarios. For the PQ plot, the capability is recorded while sweeping the active power production of the wind farm from 0 to 100%. For the UQ plot, the capability is recorded (at full production) while sweeping the grid voltage from 0.95 to 1.05 p.u.. The STATCOM is considered as a constant-current source capable of operating between 0.8 p.u. and 1.2 p.u.. For simplicity, no STATCOM transformer is modelled.

Fig. 4a) shows the PQ capability of the wind farm system. The plot shows that a STATCOM of 140 MVAR is necessary to cover the entire capability envelope. Fig. 4b) shows the UQ capability. The plot confirms that a STATCOM of 140 MVAR is necessary.

However, the results shown in Fig. 4a) and b) cannot guarantee a sufficient capability alone. The grid codes often specify that the reactive power response of the system must be within e.g. 1 second. The tap changers typically use 3-5 seconds, and this is for each tap. Consequently, the OLTCs will not contribute to the required dynamic voltage support. For example, if there is a grid voltage step from 1.0 p.u. to 0.95 p.u., the undervoltage will remain in the system during the first second. The undervoltage influences the reactive power of the system, for example the capability of the STATCOM. The capability given in the UQ plot does not capture this time response limitation of the OLTCs as it shows the steady-state capability after the transformer OLTCs have tapped to achieve their control setpoints.

Therefore, to ensure the plant has the required capability within 1 second, a third plot type is created. This plot, referred to as a dynamic UQ plot, is shown in Fig. 4c) and d). These plots show the capability of the plant during a voltage step with fixed OLTC taps. All voltage steps up to and including the most demanding voltage step should be considered to guarantee compliance. The most demanding voltage steps considered for the UK are between 1.05 p.u. to 0.95 p.u.. To guarantee compliance both a voltage step down (Fig. 4c)) and step up (Fig. 4d) are checked.

The initial conditions before the voltage steps must be determined before doing the sweeps. These are found using a load flow analysis. For example, to find the tap positions for the sweep when stepping down, it is assumed that an overvoltage of 1.05 p.u. in the grid has been present long enough for the wind farm system to reach steady-state conditions. It is assumed that the STATCOM is reacting to the overvoltage and consuming reactive power so that the reactive power in the interface point is Q_{min}. The OLTCs have tapped to reach their control setpoints. The tap positions determined for the initial conditions are shown in TABLE III. The square brackets indicate the taps for each of the STATCOM ratings: STATCOM 1 = 120 MVAR, STATCOM 2 = 140 MVAR and STATCOM 3 = 160 MVAR. The STATCOM rated 120 MVAR is not sufficient to reach the Q_{min} setpoint in the grid interface point. Therefore, the taps for this STATCOM rating are slightly different than for the other ratings.

TABLE III
DYNAMIC UQ PLOT TAPS

Equipment	Step down	Step up
Onshore shunt reactor	[+1, +1, +1]	[0, 0, 0]
Onshore transformer	[+2, +2, +2]	[-1, 0, 0]
Offshore transformer	[+4, +4, +4]	[+4, +3, +3]

Notation: [STATCOM 1, STATCOM 2, STATCOM 3]

Fig. 4c) show that a STATCOM of 140 MVAR will not give the required capability after a voltage step from 1.05 p.u. to 0.95 p.u.. The figures show that a STATCOM rating of at least 160 MVAR is necessary.

IV. USING EQUIPMENT WITH ASYMMETRIC REACTIVE POWER CAPABILITY

An equipment with asymmetric voltage capability, that is, equipment that does not have the same capability in the capacitive and inductive range, might be used to comply with the voltage support requirements. A typical example is a synchronous condenser. A synchronous condenser has the required time response for voltage support, but the reactive power capability range of the synchronous condenser is asymmetrical. Its range is typically 100% in the capacitive direction, but only 50% in the inductive range. In contrast, the STATCOM has equal capability in both inductive and capacitive range. When the equipment used for voltage support has an asymmetrical reactive power capability, there is a risk of oversizing the equipment to comply with the capability of the limited range.

This oversizing can be avoided by adjusting the compensation scheme used for the shunt reactors. Instead of controlling the variable shunt reactor to achieve 0 MVAR reactive power in the grid interface point, the control setpoint can be given an offset. The offset must be set so that the overall dynamic reactive power capability is symmetric, despite the asymmetrical range of the voltage support equipment. The rating of the variable shunt reactor must be re-evaluated so that it has the required capability to achieve the offset.

Fig. 5 shows the result of using an equivalent synchronous condenser. The equivalent synchronous condenser is connected to the 220 kV bus by a 180 MVA 220/11 kV transformer with a series impedance of 12.5% and X/R ratio of 40. The equivalent synchronous condenser can be either one large or a group of several smaller synchronous condensers. A control setpoint of $-39\ \mathrm{MVAR}$ has been used to offset the plant capability. The rating of the onshore shunt reactor is increased by 40 MVAR so that tap nr. 0 is equal to 230 MVAR and tap nr. 10 is equal to 330 MVAR to handle the increased demand of the offset. The plot shows that an equivalent synchronous condenser of at least 190 MVAR is necessary. The rating should be further verified in a dynamic UQ plot to show that the system capability is sufficient within 1 second. The dynamic UQ plot is not shown here as the same procedure as described in the previous chapter can be used.

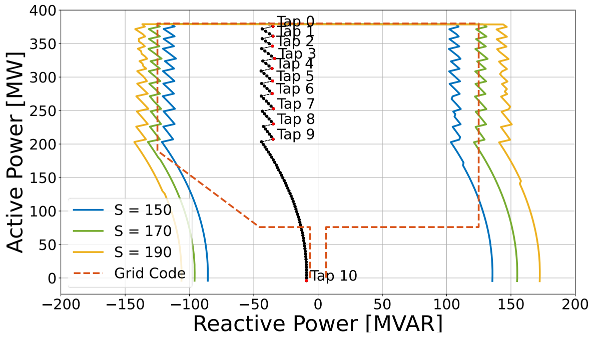


Fig. 5 PQ capability with synchronous condenser.

V. CONCLUSIONS

This paper has presented a procedure for determining the reactive power compensation scheme for an AC-connected wind farm. The following design criteria have been used:

1. A fixed offshore shunt reactor has been sized to get the desired current distribution in the HV transmission cable.
2. A variable onshore shunt reactor has been sized to compensate the wind farm system and the variation of reactive power with the active power produced.
3. A STATCOM has been sized to comply with voltage support requirements from the grid codes.

The procedure has been demonstrated for a 400 MW wind farm system. It is also shown how the rating and control setpoints of the variable shunt reactor can be changed to adopt for a voltage support equipment with asymmetrical reactive power capability such as a synchronous condenser. The required parameters for the compensation scheme as determined for the example system are shown in TABLE IV.

TABLE IV
PARAMETERS OF THE COMPENSATION SCHEME

Equipment	STATCOM	Synchronous condenser
Offshore shunt reactor	180 MVAR	180 MVAR
Onshore shunt reactor	190-290 MVAR	230-330 MVAR
Q control setpoint	0 MVAR	-39 MVAR
STATCOM	160 MVAR	N/A
Synchronous condenser	N/A	190 MVAR

VI. REFERENCES

[1] NESO, 2025 *THE GRID CODE*, Issue 6, revision 36.

[2] D. Wu, et al., “Grid Integration of Offshore Wind Power: Standards, Control, Power Quality and Transmission”, *IEEE Open Journal of Power Electronics*, Volume 5, pp 583-604 2024.

VII. VITA

Egil Viken graduated with a MSc from the Norwegian University of Science and Technology (NTNU), Trondheim, in 2020. Between 2020 to 2022 he worked as an assistant professor at NTNU Ålesund. Since then, he has been working as a power system engineer in ABB. He has experience from AC power from shore systems and offshore wind farms.
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