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Reactive Power Compensation Considerations for Offshore AC Networks

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SUMMARY

Offshore wind farms are generally integrated into bulk power grids at the onshore point of common coupling (PCC) through the AC submarine cable. The stability of system network operation with a large penetration of wind energy has been one of the most important issues. The voltage stability of the grid is affected due to the reactive power compensation scheme and the devices used. The reactive power (Q) controls involve voltage regulation with or without active power (P) generation, reactive power (Q)/power factor (pf) control, and fault ride-through capabilities. This paper discusses important aspects of reactive power contribution as well as reactive power compensation of the offshore AC network.

The dynamic performance of the wind power plant (WPP) is dependent on how the individual wind turbine is contributing to voltage control as well as the voltage fluctuation throughout the WPP during transients. Through the control actions of an overall park controller, wind turbines (WTs) can make use of their reactive power capabilities. On the other hand, the cable itself can be looked upon as a VAr source (capacitive) that supplies reactive power into the grid. The charging current in AC cable is voltage dependent, the higher the voltage, the faster the transmission capacity will drop as a function of the cable length. The reactive power of the cable system needs to be compensated wisely to achieve a stable, secure, and economical operation of the transmission grid.

Reactive power is generally produced or absorbed by major components of a power system. The rating of the compensation equipment depends on the system configuration, wind plant's generation capacity, type of wind turbines, and rating of the FACTS devices. To keep the operating voltage within acceptable margins, an optimal cost-effective reactive power compensation solution is necessary. In conclusion, this paper suggests general task requirements for planning and optimization of the reactive power compensation in an offshore AC network.

KEYWORDS

Offshore wind, voltage stability, reactive power compensation, dynamic performance, wind power plant (WPP), wind turbines (WTs), charging current, FACTS devices

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BACKGROUND

With growing concerns over climate change and fossil fuel depletion, the exploitation of renewable energy has become paramount in electricity generation [1]. Currently wind energy is the fastest-growing power generation resource. According to [2], the worldwide wind capacity reached 744 Gigawatts (GW) – an unprecedented 93 GW growth in the year 2020 alone. The installed capacity of wind power in North America reached about 136 GW (122 GW by USA) in 2020 [3]. In recent years, the number of installed offshore wind plants has increased rapidly while many larger wind plants are being planned. Figures 1, 2 and 3 show a typical arrangement, the topological structure, and a general electrical layout of an offshore wind farm, respectively.

Fig. 1 Offshore wind farm [4]

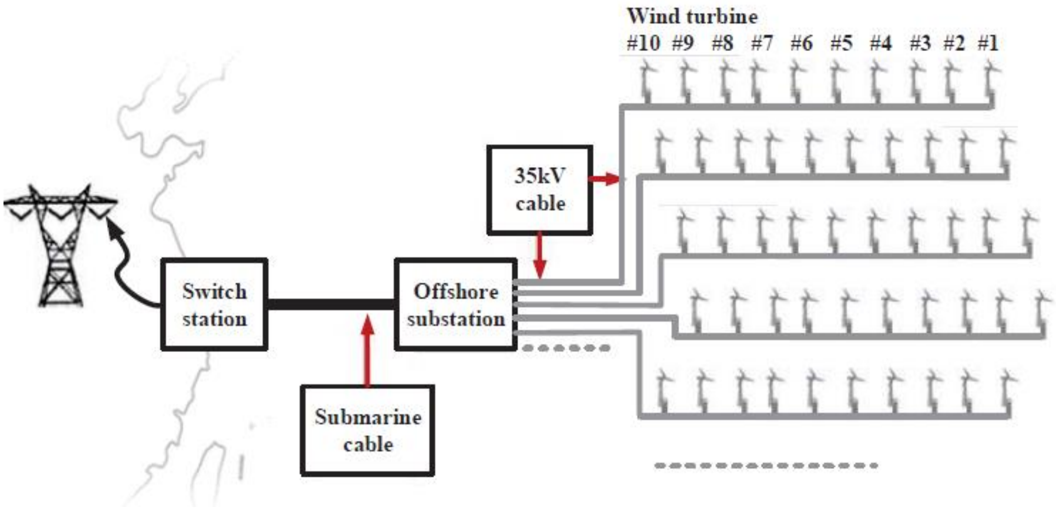


Fig. 2 Topological structure of an offshore wind farm [5]

This paper discusses important aspects of reactive power contribution and reactive power compensation of an offshore AC network. Reactive power is produced or absorbed by major components of a power system, such as generators, transmission lines (overhead or underground), transformers, loads, and reactive power compensation devices. The reactive power demand in a power system results from the reactive power consumption of the load as well as reactive power losses in the network [6]. In transmission networks, the reactive power losses depend mainly on the active power transfer and network configuration. On the contrary, in LV (low voltage) and MV (medium voltage) networks, the reactive power losses are generally low and vary with the load.

To access all relevant aspects in the complex process of designing large offshore wind power plants (WPPs), several system studies need to be performed [7]. That include:

- Grid codes compliance, such as: reactive power requirements, steady-state and dynamic stability performance, low voltage ride-through capabilities, power system oscillations, inertial response, harmonic performance, etc.
- Ratings of WPP and export circuit component,
- The extent of reactive power support a WPP can provide, and
- Protection and safety

If supporting offshore wind planners or developers, it is important to review the following points:

- What are the main sources that contribute to reactive power in offshore AC networks?
- What are the reactive compensation requirements for a proposed offshore AC network and how will they be met?
- Is the shunt compensation for the offshore cable circuit installed at onshore substations only or both at the offshore and onshore substations?

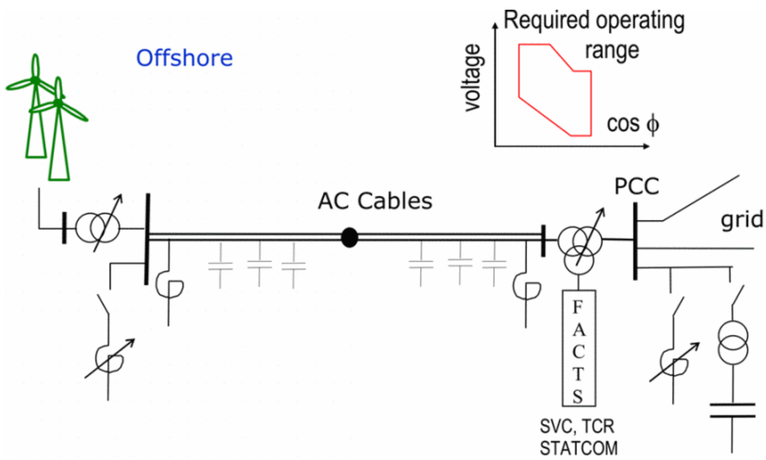


Fig.3 General layout of an offshore wind farm [8]

Wind power plants (WPPs) are commonly grid connected; they need to fulfill grid codes or limits. Adequate reactive power reserve of WPP is critical to handle steady-state and transient-state uncertainties and maintain the electric grid's stability and power quality requirements [9].

The grid codes of transmission system operators (e.g., ISO/RTOs in North America) generally set the system voltage stability requirements at the respective voltage levels. The grid codes/limits define some requirements on the frequency/active power control, voltage/reactive power control and system performance under fault conditions. Under the direction of utility grid codes, offshore wind plants can be able to handle specific power system contingencies, including short circuits, power system oscillations and loss of generation. The grid code requirements vary from one jurisdiction (system operator) to another, but there are some common aspects [10]. For the most part, the offshore WPPs control requires : i) active power/frequency control, ii) reactive power/voltage control, and iii) low voltage ride-through (LVRT)/fault ride-through. WPP controls can coordinate the P and Q response of multiple wind turbines (WTs) and thus make the plant control function as a single integrated power generation source.

In steady-state, the voltage at the onshore PCC can be restricted within a certain range. In case of a contingency, system operators would require the WPPs to remain connected to the grid under the worst-case of voltage dip. Voltage should be recovered after the clearance of faults/disturbances. Primarily, the WPP should be able to operate with different setpoint voltages and slopes, according to grid code requirements. The grid code requirements determine the Qmax and Qmin values (as shown in Fig. 4) and they are dependent on the wind plant's rated active power (P) [7].

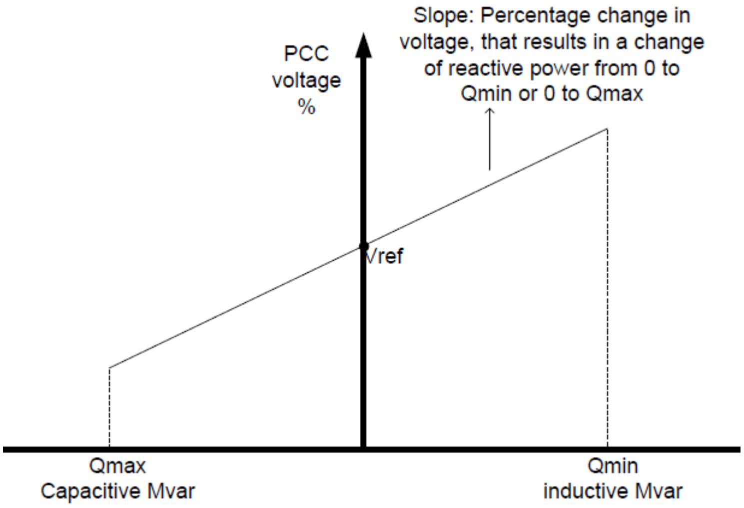


Fig.4 Voltage control droop characteristic at the PCC [7]

REACTIVE POWER CONTRIBUTION BY WIND TURBINE GENERATORS

The wind turbine generator (WTG) technologies that are being deployed offshore consist of directly connected fixed speed wind turbines, variable speed generators with partially rated power converters and variable speed generators that connect to the network through full-scale power converters [7]. These generators have the capability to control reactive power by varying excitation either to leading power factor (i.e., capacitive) or lagging power factor (i.e., inductive) according to the system requirements.

The dynamic performance of the WPP is dependent on how the individual wind turbine is contributing to voltage control as well as the voltage fluctuation throughout the WPP during transients. The dynamic performance has an influence on how the reactive power compensation of the wind power plant is designed and rated [4]. Through the control actions of an overall park controller, wind turbines (WTs) can make use of their reactive power capabilities. Usually, two different control modes are employed, namely reactive power control and voltage control - as discussed in CIGRE TB 483 [7]. The phase angles of the synchronous machines are adjusted to produce reactive power (i.e., capacitive, or inductive) by varying machine excitation.

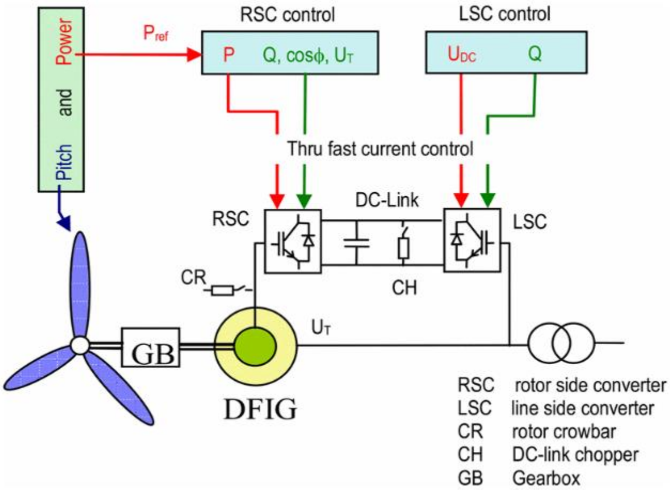
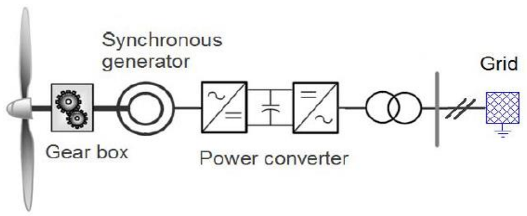
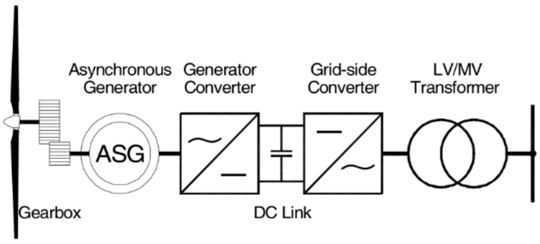


Fig. 5 Configuration of a WT equipped with DFIG [8]

The commonly used WTs are equipped with doubly fed induction generators (DFIGs) (Fig. 5 [8]); the synchronous generator (SG) equipped with a full-scale power converter [10] and an adjustable speed generator (ASG) equipped with a full-scale frequency converter [11] as shown in Figs. 6a) and 6b). These generators have considerable differences compared to the traditionally used grid-connected synchronous generators.



a)



b)

Fig. 6 a) Example of a WT equipped with SG and full-scale power converter [10] and
b) WT equipped with induction generator and full-scale frequency converter [11]

DFIG-based wind turbines can supply the reactive current required according to the grid codes using rotor and line side converters (i.e., RSC and LSC) control. Reactive power capability at individual DFIG depends on six variables - the maximum capacity of stator current, the maximum capacity of rotor current, rotor voltage, winding factors, magnetic saturation, and reactive power of grid side converter (GSC) or line side converter (LSC). Fig. 7 shows the reactive power capability of a DFIG with respect to (w.r.t.) stator current limit and Fig. 8 shows the reactive power capability of a DFIG with and without GSC's reactive power capability [9].

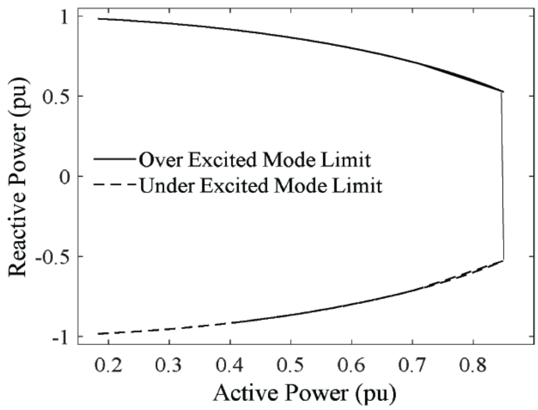


Fig. 7 VAr capability w.r.t. stator current limit [9]

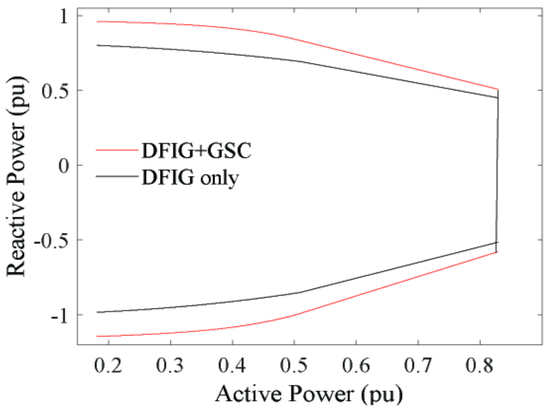


Fig. 8 VAr capability with GSC [9]

As large-scale wind plants with different types of wind turbine generators (WTGs) become more and more important in the role of mixed power generation, these generators shall be included in the power system dynamic performance studies [10]. It is necessary to maintain the stability of power systems with large wind power penetration to ensure a reliable power system operation.

REACTIVE POWER CONTRIBUTION BY AC CABLES

The cable itself represents a VAr source (capacitive) that supplies reactive power into the grid. With slightly under-compensated cables, it is likely to provide a sizeable contribution to VAr generation. In offshore AC networks, the aim of reactive power compensation is to boost the transmission capacity of the cables, reduce the losses and ensure a stable system voltage [4].

AC cable links are characterized by many times as large shunt capacitance compared to overhead lines. The resulting charging current will limit the remaining cable ampacity for active power transfer, increase the active power losses and increase the voltage along the line due to the Ferranti effect [11]. The charging current is voltage dependent, the higher the voltage of the cable system, the faster the transmission capacity will diminish as a function of the length. It also depends upon the capacitance per unit length. Fig. 9 below illustrates the loading of an open-ended cable line due to the charging current for various distributions of the reactive power compensation along the line.

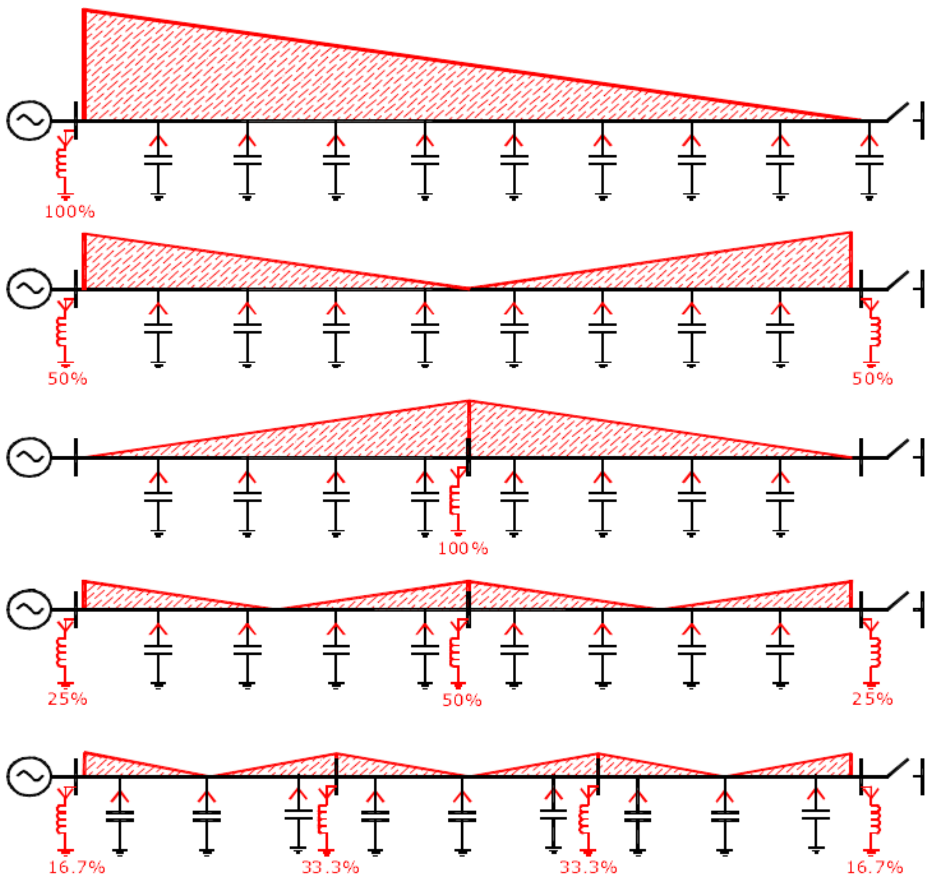


Fig. 9 Loading of an open-ended cable line and schemes for reactive power compensation [11]

At a critical length of the cable, the current rating is completely consumed by the capacitive current and no active power can flow through the cable. Shunt compensation along the cable circuit can resolve this problem. The VAr amount and the location of shunt compensation can influence voltage profile along the cable as illustrated in Fig. 9 [11].

Reactive power (VAr) surplus in any operating condition causes a power-frequency voltage rise, not only at the cable terminations but also at the adjacent substations of the grid. In normal operating conditions, a certain voltage step is usually allowed while connecting or disconnecting a cable as specified in grid code or the planning/operational criteria of the system operator as discussed in [12].

In Fig. 9, as illustrated, the length and transport capability of the power cable are impacted by reactive compensation either at the onshore substation, at the offshore substation, or both ends and for very long lengths in the middle. The optimal way of operating a cable would be to strive for an equal charging current at each end of the cable [4]. To keep the operating voltages within acceptable margins, an optimal cost-effective reactive power compensation is necessary. Such compensation can be achieved by using shunt reactors, typically at both ends (with 50%/50% compensation) of a cable (as shown in Fig. 10). Fig. 10 illustrates the influence of reactive power compensation for a 1200 mm² copper 220 kV HVAC three-core submarine cable system [4].

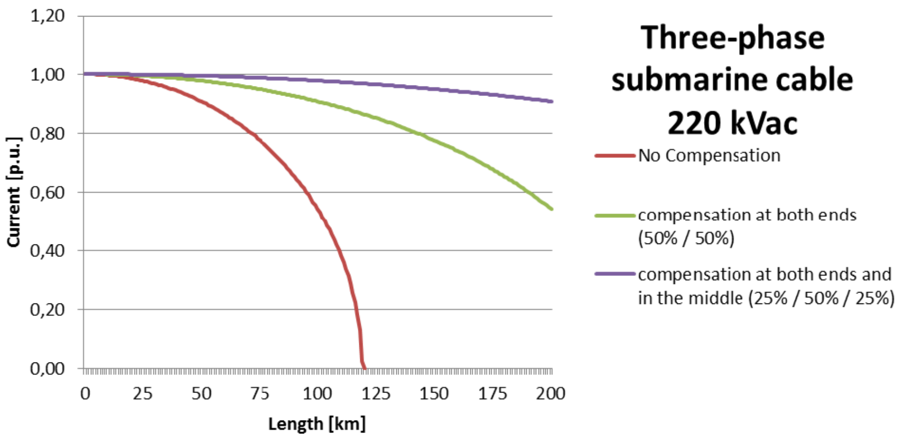


Fig. 10 Influence of compensation on a three-core 220 kVac submarine cable system [4]

REACTIVE POWER COMPENSATION

The charging current distribution along the cable length can be improved by using compensation equipment facilitating an equal current flow at both the generation and load ends. Further improvement is possible by locating additional shunt reactors at the offshore substation along the cable circuit. However, this is an expensive solution for offshore platform costs, normally not used for cables at sea [4].

The following reactive power compensation devices are commonly used:

- Mechanically switched shunt reactors (MSR)
- Variable shunt reactors with tap changers
- Thyristor based Static Var Compensators (SVC)
- VSC based SVCs or Synchronous Static Compensators (STATCOM)

The need and rating of the compensation equipment depend on the system configuration, wind plant's P&Q generation capacity, type of wind turbines, distance to shore (between the onshore and offshore substation), voltage and power rates, transformer impedance and other equipment such as harmonic filters [4]. The costs for the compensation are predominantly voltage dependent; compensation devices at higher voltages are more expensive than compensation devices at lower voltages.

CONCLUSION

Switching of a long high voltage AC cable can cause overvoltage if the cable system is not properly compensated. The reactive power of the cable system needs to be compensated prudently to achieve a stable, secure, and economical operation of the transmission grid. Under steady-state operation, reactive power sources, such as VAr generation by wind turbine generators, switchable capacitors or reactors (such as, MSC, MSR, MSCDN), SVC, STATCOM, harmonic filters, etc., as well as equipment impacting the VAr demand indirectly like transformer's on-line tap changer (OLTC), can be controlled effectively to achieve the minimum active power (P) loss while fulfilling the grid code. Wind power output depends totally on the availability of wind and the wind generator output will vary with time. If more than one wind plant's array cable is available, cables can be switched off during low power generation to control the reactive power of the cable system [8].

Planning and optimization of reactive power compensation for offshore AC connection is a part of the overall planning of the system [6]. Thus, planning for the reactive power resources and compensation is a complex and comprehensive task. The task generally involves the following:

- the total amount of reactive power resources to be installed,
- reactive power distribution along the circuit, location of the devices, and voltage levels, and
- its subdivision into different types of reactive power devices to support steady-state and dynamic stability.

The task also involves the assessment and allocation of reactive power reserve necessary during system instability or disturbances.

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